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NRL Report 7302

Proceedings of the Workshop on Naval Applications of Superconductivity

November 4-6, 1970
Naval Ship Research and Development Laboratory
Panama City, Florida

Sponsored by

CHIEF OF NAVAL RESEARCH AND CHIEF OF NAVAL DEVELOPMENT

July 1, 1971

NAVAL RESEARCH LABORATORY
Washington, D.C.

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Edited by
J. E. COX AND E. A. EDELSACK

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Preface

This workshop on Naval Applications of Superconductivity was jointly sponsored by the Chiefs of Naval Research and Naval Development. Present were representatives, military and civilian, from research and development groups in the Navy concerned with present and future applications of superconducting materials, devices and systems. For the first time, engineers, administrators, scientists and fleet personnel—all with a common interest in superconductivity—met in one place for a period of two and one-half days to engage in a free and frank exchange of ideas, to review existing programs, and to discuss future plans. In addition, the workshop provided an unique opportunity to collect the opinions and comments of experts from industry and universities regarding the current status and future prospects of various areas of superconducting technology which relate to naval requirements.

The program was divided into two parts, with a total of seven sessions. Part I, consisting of four sessions, was unclassified and contained ten invited papers plus discussion and summary. There were about 95 persons at these sessions, including Navy and non-Navy attendees. Part II, consisting of three sessions, was classified secret and contained some 21 contributed papers. Attendance at these three sessions was limited to Navy personnel, who numbered about 75.

Topics for the invited talks and the general planning of the workshop were the responsibility of the program committee. The chairman and program committee are indebted to the following invited speakers, whose presence, presentations, and lively discussion made for a stimulating and informative meeting:

Dr. Edward Takken	Dr. Sidney Shapiro
Dr. Robert Rose	Dr. William Goree
Dr. John Daunt	Dr. James Mercereau
Mr. C.J. Mole	Dr. James Nicol
Dr. David Coffey	Dr. Donald Langenberg

The contributed papers were presented by representatives of seven Navy Laboratories and Centers, the Naval Ship Systems Command, and the Office of Naval Research.

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The manuscripts of the talks were either directly supplied by the speakers or were edited by the speakers from transcriptions of their recorded talks. The proceedings have been prepared for publication at the Naval Research Laboratory and are issued as NRL Reports 7302 and 7303. The first report is unclassified and contains the invited papers given in Part I in the order in which they were presented, followed by a summary and lightly edited discussion. This report also contains a few of the contributed unclassified papers which were presented in Part II. The second report, classified secret, contains all classified papers presented during Part II, plus those unclassified papers whose subjects relate to material discussed in the classified papers. The material presented in the classified sessions is included in its entirety, with the exception of information of a management nature.

The hospitality of the Naval Ship Research and Development Laboratory at Panama City, Florida, will long be remembered by all those who attended this workshop. Dr. Robert Allen, Acting Technical Director, and Dr. John Wynn, Chairman, local arrangements, deserve special thanks for their enthusiastic handling of all local arrangements. They were ably assisted by:

Visual Aids: James Durden
T. C. Johnson
Stanley Myers

Registration: Marilyn Griffin
Lynda Coram

Security: T. L. Patterson

Transportation: R. E. Holland

Conference Secretary: Sandra Brahier

It is a pleasure to acknowledge the efforts of the following individuals who significantly contributed to the success of the workshop:

Donald Gubser, NRL, conference recording.

Warren Ramey, Robert Clark, Irving Rudin, and staff, NRL, for the design, editing, and printing of the announcements, program, and proceedings.

Kenneth Klausing, Graphic Arts Branch, NRL, for the photography at the workshop.

Barbara J. Moreland, Norma Siironen, and Deborah Revis, for their patience, fortitude, and expert assistance with the avalanche of secretarial and administrative chores that preceded the meeting.

Joan Thorne for transcribing the tapes and typing many of the final manuscripts.

Finally, a note of personal thanks to:

Dr. Elliot Weinberg, ONR, and Mr. Frank Isakson, ONR, whose continued encouragement provided that ray of hope often needed to overcome administrative obstacles.

Dr. Richard Brandt, ONR Pasadena, for leading a very stimulating discussion and presenting a lucid review of Japanese superconducting technology. Dr. Brandt's report, "Superconducting Technology in Japan," ONR Report 28, provides a fuller account of his recent survey of Japanese progress in this field.

Dr. Robert Hein, NRL, who interrupted a very busy schedule in ONR London to participate actively in the workshop and to summarize recent developments in superconductivity in the U. K.

Mr. Thomas Dowd, ONR Boston, whose mature advice and guidance during the planning and organization of the workshop and whose constant assistance during the actual meeting made the task of chairman a relatively simple one.

Mr. John Cox, who has earned a lasting debt of gratitude for his efforts in making this meeting a reality and a success. His constant help in organizing and administering the workshop and in editing the proceedings shall long be remembered.

E. A. EDELSACK
Chairman

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WELCOME

Robert C. Allen
Acting Technical Director
Naval Ship Research & Development Laboratory
Panama City, Florida 32401

Good morning and welcome to Panama City, the Lab and of course most especially to the Conference. I see Cmd. Quinn and I have thirty minutes. I don't know what he is going to do with his twenty-eight but that's his problem. I do want to say that we are really very honored to have the conference here and from our part we will do everything we can to make your stay very pleasant. So in that sense please feel free to call upon John Wynn or myself or "Miss Southern Comfort" for any of your requirements and anyway we might help. The purpose of the three days is of course to review in rather significant detail what's going on in the Navy in superconductivity. However, I hope that some time during the three days you will be able to find out a little bit more about what goes on at the Laboratory. John has arranged a tour tomorrow afternoon which I think will be convenient for those who are going to participate in today's and tomorrow morning's sessions. It may also be convenient for some of the others. In addition, after the dust settles, Friday afternoon we will be available to conduct other very informal tours of the laboratory and we hope very much as many as possible can participate in walking around the laboratory and finding out a little bit more about what we do. So gentlemen please feel free to call on us in any way that you feel is necessary. We are here to be of assistance. Welcome and thank you.

OPENING ADDRESS

Commander R. T. Quinn, USN
Naval Ship Systems Command
Washington, D. C. 20360

I think this is going to be the shortest thirty-minute introduction you ever had because I have about five minutes worth of things I want to say.

First of all it is a real pleasure for me personally to be back in Panama City. I served about 18 months down here on one of the little mine sweeps that provide service to the laboratory. That was about fifteen years ago. Many changes have occurred since then both to this laboratory and to the ships of the fleet.

We are here today to discuss an exciting new technology that's coming down the pike and in applying this technology to our future ships of the fleet, hopefully before another fifteen years has passed. In the current days of cutbacks in our budget and DOD's, it is imperative that each of us in R and D look at potential technologies which promise great benefits for our ships of the future. Certainly most of us here today believe that superconductivity and its application to our ships is such a technology. It's been a long time since 1911 when Onnes first discovered that certain metals near absolute zero became almost perfect conductors. For the next forty years, however, superconductivity was merely a laboratory curiousity. Since the elemental metals found to be superconducting near zero could carry very little current before they lost their superconductivity because of the magnetic field surrounding them, we were well into the 1950's before the discovery of the intermetalic compounds which constitute today's superconducting materials. This was just

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before my mine sweeping days, really.

There, again, superconductivity became a practical application or looked like it might have practical applications but even then it has taken us some ten years to solve the technical problems of these new brittle materials, and how to fabricate them into useful wire. For the past few years of course the translation has occurred in superconducting technology primarily in the research laboratory of the people working in high energy physics. By making such applications as bubble chambers, the beam handling systems and the accelerators. The applicability of superconductivity for fleet use is just beginning to emerge. The program for this symposium suggests many applications to be approaching practicality and even more of yet undisclosed potential.

The technology is finally entering the realm of higher applications. Today we find an interest in NASA in electric propulsion and magnetohydrodynamic space power generation, in the Dept. of Transportation, propulsion and magnetic levitation of trains for transportation; in industry we find that large stationary plant applications are of interest, also their transmission line problems; in the Dept. of Defense we find that the electric power systems for aircraft, electrical propulsion for wheeled vehicles and special applications in our ships and the generating systems, in the mine sweeping systems and in the ships propulsion applications. In the Naval Ship Systems Command we are very interested in the application of superconductivity to the propulsion machinery. We see here an opportunity to use the flexibility and versatility of electrical machinery for a propulsion transmission and with machinery which can compete on a weight, space and cost basis with the traditional geared drive of our ships. It wasn't too long ago when we in management positions were shocked when the researchers came in promising to give us machines of several thousand horsepower which would fit into a shoebox. Needless to say, they have not delivered the shoebox much less the machinery that fits into it. However, our investigations and our studies have convinced us that we can successfully develop high horsepower and propulsion machinery with very promising weight and volume to horsepower ratios. This has only become possible in the very recent past due to the availability of the highly stable superconductor materials that were developed for the research programs that I mentioned earlier. Looking over the credentials of the people who are here at the conference, one must be astounded at the diversity of the people that are in this audience. Represented here of course are the basic researchers, the materials and the electrical side of the problem, the engineers from some of our laboratories and their customers. Considering this I am very pleased. It is not often that such a diverse group can get together and exchange ideas and cross fertilize each other if you will. I hope we can make this an opportunity for each side to learn what the other wants. The researchers to learn what the customer desires and needs and I hope the customers will come from this meeting with an understanding of the potential that lies ahead for superconducting technology. In spite of the diversity that might exist among our particular jobs, I think there is a common denominator; everyone here is concerned with the fostering of the application of superconductivity to the future requirements of our Navy. Thank you very much.

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SESSION A

Wednesday Morning, 4 November 1970

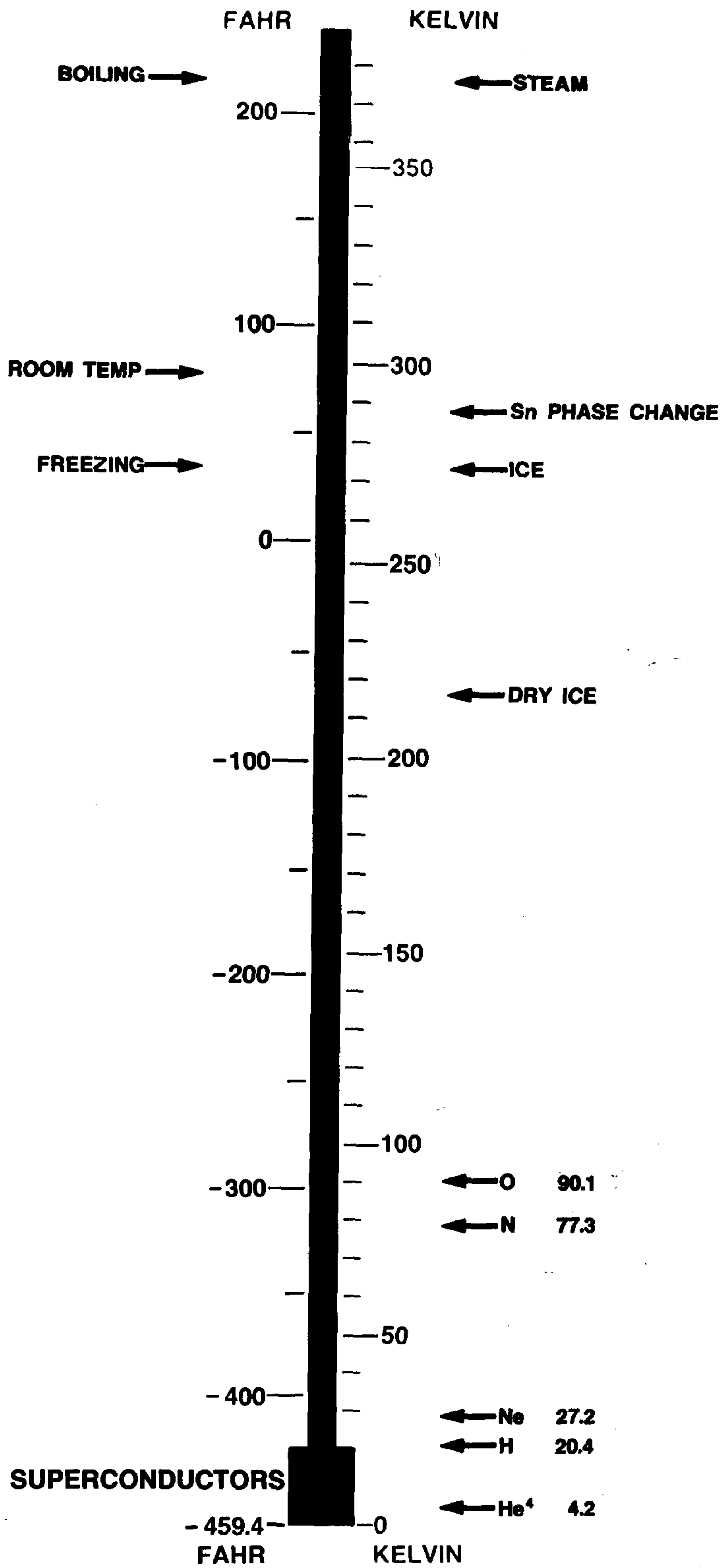
Chairman: R.A. Hein
Naval Research Laboratory

PROPERTIES OF SUPERCONDUCTORS

Edward H. Takken
Naval Research Laboratory
Washington, D.C., 20390

The purpose of this talk is to give an introduction to the fundamental terminology and properties of superconductors. Let's begin by talking about how very cold a metal has to be before it becomes a superconductor. Fig. 1 shows representative temperature scales, the Kelvin on the right and the more familiar Fahrenheit on the left. The boiling and freezing points of water are up at the top of our scales. We will refer loosely to arctic temperatures as the region from zero down to, say, - 100 degrees Fahrenheit. Dry ice falls in this temperature range, and so does an interesting phase change of tin. As it undergoes this phase change, tin turns from a bright shiney metal into a dull, easily powdered substance. Tin buttons tend to crumble in arctic temperatures, and, indeed, legend says that this is exactly what happened to the uniform buttons of Napoleon's army during the invasion of Moscow.

Our point here is simply that arctic temperatures are very <u>hot</u> compared to the cold temperatures where superconductivity occurs. Absolute zero is about -460 on the Fahrenheit scale. Usually when we talk about cryogenics in the laboratory, we refer to a dewar holding liquid helium at four degrees Kelvin or below. In some metals superconductivity exists up to somewhat over 20° K, and, of course, people are continually trying to find superconductivity at higher and higher temperatures where cooling would be easier. The task is becoming increasingly difficult as we will explain shortly. On the other hand refrigeration technology is improving significantly, both for large and for small systems, so that it becomes reasonable to



FAHR
KELVIN
BOILING
STEAM
200
350
100
ROOM TEMP
300
Sn PHASE CHANGE
FREEZING
ICE
0
250
DRY ICE
-100
200
-200
150
100
-300
O 90.1
N 77.3
50
-400
Ne 27.2
H 20.4
SUPERCONDUCTORS
He4 4.2
-459.4
0
FAHR
KELVIN

Figure 1.

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talk about field applications of superconductors even though they do require such an especially cold working environment.

There are three basic properties that define superconductivity -- zero resistance, the Meissner effect, and quantum phase coherence. Zero resistance simply means that electrical current can flow through a superconductor with zero applied voltage. Meissner's experiment showed that magnetic fields are expelled from superconductors. This isn't always true though, and it is necessary to distinquish, as we will explain later, between what are now called type I and type II superconductors. The idea of quantum phase coherence is too abstract to explain here, but we will discuss how it shows up in the Josephson's relations and hence in today's "micro-superconductor" electronics.

ZERO RESISTANCE

Zero resistance was first observed by Kamerlingh Onnes in 1911, but it's theoretical explanation came almost half a century later in 1957. As you cool down a normal metal, its resistance decreases as shown by the dotted line in Fig. 2a. For superconductors the resistance drops precipitously, in fact, to zero at the transition temperature T_c as shown. In a normal metal with current flowing through it, the current is proportional to voltage. For a superconductor cooled below its transition temperature current can flow with zero voltage across the sample as shown in Fig. 2b. If you push the sample too hard with too much current, though, and usually it requires a very large current, the superconductivity can be destroyed as shown. However, the point is that for reasonable currents and at low enough temperature, some metals are superconductors showing zero resistance with current flowing under zero voltage.

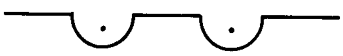
Well, how about a circular current in a superconducting ring? Can there be a magnetic field maintained by perpetual currents that last forever? This kind of current loop has been monitored for two and a half years with no observable decay of the field. There was no detectable resistance, and the limitation of the experiment was simply that a graduate student finally forgot to refill the helium dewar.

Of course, we can't really measure zero in an experiment. Quantitatively, what has been determined is that the resistance of a superconductor is 10^{-14} times that of room-temperature copper.

Figure 2.

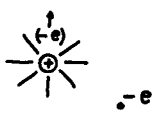
2a. R(T) vs. T   2b. I(V) vs. V

Figure 3. The "weak bed model."



3a. Indentations not overlapping.

3b. Indentations overlapping.



3c. Lattice polarization due to electrons.

4a.

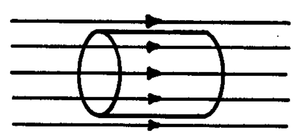
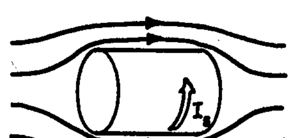
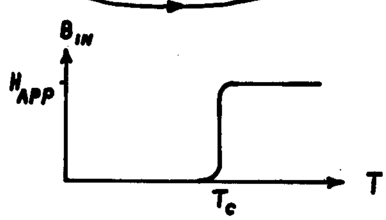


Figure 4. A superconducting cylinder in an applied magnetic field.

4b.



4c.



For all practical purposes this is verification of the ideal zero resistance.

The liquid helium used to cool the first superconductor way back in 1911 came from gasses extracted from a special sand that had to be shipped all the way from India to the Netherlands. We are a far cry from that meager beginning today. The superconducting magnet business currently runs between two and three million dollars annually. By 1980 superconducting motors and generators will probably run the market up to at least twenty million.

The property of superconductors used in magnets and machinery is simply low ohmic losses or zero resistance. Many of the electronic devices use the more subtle phase coherence properties of superconductors, and there is reason to expect some of these to have a considerable influence on our electronics industry.

But how can there be superelectrons that experience no resistance to their motion along the wire? The answer is that in a superconductor each electron of momentum p and spin up ($\uparrow$) forms a bound pair with another electron of momentum -p and spin down ($\downarrow$). These electron pairs are bound together with an energy denoted by Δ, and it's because of these unbreakable bonds that the electrons suffer no resistance as they move down the wire. For an electron to suffer scattering, it would first have to be broken apart from its pair, but this can not happen for reasonable currents for which the kinetic energy is small compared to the binding energy Δ.

The force that holds these electron pairs together is a lattice mediated force, V, which is perhaps best explained by an analogy often referred to as the "weak bed model." This is simply that when two people lie on a bed together there seems to be an attractive force between them. Now, as we all known, the explanation of this phenomenon is simply that the weight of each body pushes down an indentation in the mattress as shown in Fig. 3a. If they get too close together these indentations begin to overlap, as in Fig. 3b, and each person tends to roll into the indentation caused by the other, so that there is an attraction between them.

The same sort of thing happens for electrons in a crystal lattice. Because they are of opposite electrical charge, the lattice ions and conduction electrons attract each other. An electron polarizes the lattice, pulling the ions together as indicated in Fig. 3c. When this electron moves away, it leaves behind a momentary plus charge in the polarized lattice. Then a second electron is attracted by this distortion and hence to the first electron.

By way of terminology, let me point out that this lattice mediated attraction is referred to as due to virtual phonon exchange. Virtual means "of the essence but not exactly the fact." A phonon is a sound wave, that is, a time oscillatory vibration of the lattice. Well, this electron attraction is due more to a momentary distortion of the lattice rather than to oscillations, so the lattice mediated force is referred to as due to virtual phonon exchange, because there aren't really any vibrations involved in the attraction process.

Of course, everyone would like to construct materials with higher transition temperatures and higher critical fields. One of the tricks to this game is to get stronger lattice mediated attractive forces between electrons. The problem is to get a very easily deformable lattice, something like a very limp bed, without having a spontaneous change in the lattice crystal structure, or in other words, without having the bed cave in. We may never find superconductivity at neon temperatures, but $Nb_3 Al_{.80} Ge_{.20}$ is just above the hydrogen boiling point and work continues.

This idea we've been discussing, that superconductivity can occur at higher temperatures if the electron attractions are stronger, shows up clearly in the 1957 theoretical result of Bardeen, Schrieffer, and Cooper (BCS):

$$T_c = 1.14\, \theta_D \exp \{ -1/VN(0)\}.$$

Here θ_D is the Debye temperature and N(0) is essentially the electron density. For high T_c's one would like large N(0) as well as strong attractions, V.

THE MEISSNER EFFECT

Although zero resistance was observed in 1911, the Meissner effect wasn't observed until 1933. The version of the Meissner effect that we saw in the filmstrip, the suspension of a bar magnet over a superconducting lead bowl, was done in 1947.

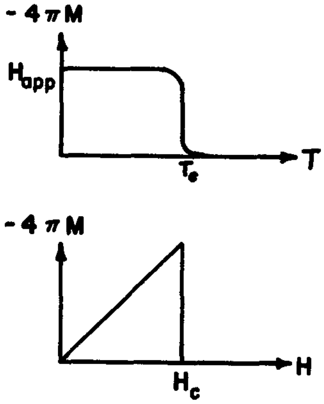


Figure 5. Magnetic moment of a long superconducting cylinder.
5a. (Top) Temperature dependence.
5b. (Bottom) Field dependence.

Figure 6.

Bar magnet over an ideal superconductor.

6a. $T > T_C$ 6b. $T < T_C$

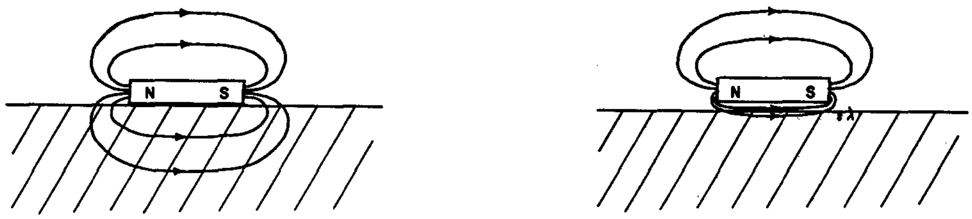
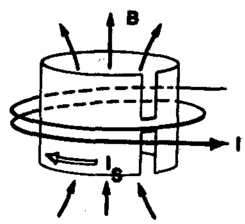


Figure 7. Flux quantization.
The flux through a superconducting cylinder must be an integer multiple of 2×10^{-7} gauss $cm.^2$



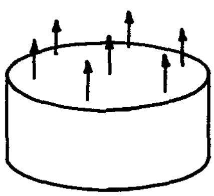
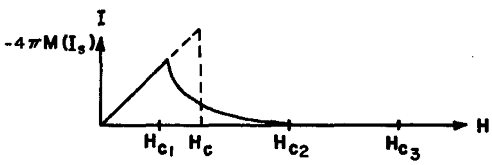


Figure 8.
A type II superconductor in a magnetic field.

8a. Flux line penetrating a sample in the mixed state when $H_{C1} < H < H_{C2}$.



8b. The resulting M(H) curve.

In Fig. 4a we see a bar of superconductor at a temperature above its transition temperature. The magnetic field inside is just the applied field H_{app}, as indicated in Fig. 4c. As the temperature is lowered below the transition temperature, B_{in} drops to zero. What happens is that zero resistance surface currents, denoted by I_s in Fig. 4b, set in to give the sample a magnetic moment M that opposes and expels the magnetic field. The internal field is

$$B_{in} = H_{app} + 4\pi M,$$

and the surface currents are just right to give an M that makes this all add up to zero.

We've plotted B_{in} as a function of T. The M due to surface currents goes just the opposite way. As shown in Fig. 5a, it's zero above T_c and then jumps up to $-\frac{1}{4\pi} H_{app}$ showing the effect of supercurrents below the transition temperature. If we change the field below T_c, I_s and M simply adjust to keep cancelling out this applied field. In other words $-4\pi M$ stays equal to H_{app}. Not surprisingly, very large magnetic fields can require more response than the sample can supply, so superconductivity with its supercurrents and the magnetic moment M are destroyed above some critical magnetic field H_c as shown in Fig. 5b. The behavior described is that of an ideal type I superconductor. As we will see later, the situation is more complicated for a type II superconductor.

ZERO RESISTANCE VS. THE MEISSNER EFFECT

Let me point out a subtlety about that bar magnet experiment we saw in the filmstrip. Actually, the demonstration showed zero resistance, not the Meissner effect. As the bar magnet is lowered down to the superconducting lead bowl, opposing currents are induced in the superconductor. Since these currents don't die out, there is effectively always an image magnet which opposes the bar magnet as it approaches the superconductor surface.

But there is another way to do the experiment. Start above the transition temperature with the metal bowl not a superconductor so that the bar magnet settles directly down on the lead bowl. Some of the magnetic field lines have to go through the metal as shown in Fig. 6a. Now, cool to below the transition temperature. If you do things right the magnetic field is expelled when the metal becomes

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a superconductor, and the bar magnet jumps up into space suspended by magnetic interactions with the supercurrents that arise spontaneously at T_c. The Meissner effect, then, is something quite separate from the zero resistance property called superconductivity.

The distance λ shown in Fig. 6b is a type of d-c superconductor skin depth. The supercurrents that expel magnetic fields are surface currents flowing within the distance λ from the surface. Since magnetic field can penetrate into this surface region, λ is called the penetration depth. It is typically on the order of a few thousand angstroms.

FLUX QUANTIZATION

Now we come to a new topic - flux quantization. Fig. 7 shows a superconducting cylinder with a wire wrapped around it in order to put a magnetic field through the hole in the cylinder. The flux Φ through this hole is the magnetic field B times the area A of the cylinder. Strangely enough this flux can not be any value you like, as for a normal metal cylinder. Even if the field doesn't touch the superconductor at all but is confined to the void in the center of the cylinder, the superconductor says that the flux has to be quantized -- that it can only take on values of some integer n times some fundamental unit Φ_o, that is,

$$\Phi = BA = n\Phi_o .$$

If you try to change the flux a little bit by putting more current through the wire, a supercurrent opposes you as shown and holds the flux at the $n\Phi_o$ value that the cylinder happens to like.

It turns out that the flux quantum is very small, $\Phi_o = 2\text{x}10^{-7}$ gauss cm^2, and this is why superconductor magnetometers are so sensitive. The cylinder shown here with the slit in the side is actually one of the magnetometers available today. Present sensitivity is about 10^{-10} gauss, which is to be compared to the earth's field of $\frac{1}{2}$ gauss and earth field fluctuations of at least 10^{-6} gauss. With some added coils these magnetometers can be used to make other types of very sensitive instruments. The femptovoltmeter, for instance, can measure 10^{-15} volts at a power level of 10^{-24} watts.

TYPE II SUPERCONDUCTORS

When we applied a magnetic field to a type I superconductor, the sample developed supercurrents and a magnetic moment in order to keep the internal field exactly zero. This was the Meissner effect. Increasing the field simply made the sample fight back harder, and we showed this on a linear graph of -M versus H. Remember that for too large an applied field the sample finally gives up and superconductivity is destroyed above H_C.

For a type II superconductor things happen a little differently. The sample fights back with its supercurrents for a while, but then at some intermediate field it begins to let through quantized flux lines as shown in Fig. 8a. Long thin filaments of the sample turn into normal metal and a flux quantum, Φ_o, of field then threads through this hole in the superconductor. (The condition for this to happen has to do with whether the surface energy between these normal and superconducting regions is positive or negative. The Russians understood this problem long before the West, and, interestingly, one of the reasons we were slow to catch on was that an important paper was dumped overboard in the New York harbor during the McCarthy era.)

Anyway, a type II superconductor gives up in bits and pieces. At the critical field H_{C1} shown in Fig. 8b flux lines begin to enter, and part of the superconductivity goes away. Finally at a much higher field H_{C2} there are so many flux lines that the normal electron cores overlap and there is no superconductivity left (except for an unimportant surface sheath that persists out to H_{C3}.)

The kind of material needed for winding magnets is one with a high H_{C2}, because in spite of the normal-conductor regions along the vortex-line cores, supercurrents can flow until we reach H_{C2}. It turns out though that there are losses if the flux lines move around, so you have to have good pinning centers for the flux lines.

THE D-C JOSEPHSON EFFECT

Now we finally come to Josephson junctions. We show in Fig. 9a two superconductors separated by a thin insulator, something like an oxide layer some 20 Å thick. Electrons can tunnel through such a barrier, and ifthese were normal metals we would observe I linear in V with a slope of 1/R. But, remember that the electrons in a superconductor are always bound in pairs. To get single electrons to flow through this resistive region one has to first supply enough potential energy to break the electron pairs apart. So, we see a curve like the one in Fig. 9b with normal current starting abruptly at the pair binding energy Δ per electron.

Now, this normal current consists of unpaired electrons tunneling through the resistive region. But what about the electron pairs? You might well suspect that there can be a supercurrent formed of bound pairs that tunnel through the oxide layer without breaking apart. This does indeed happen. The problem is subtle, and some of the results that come out in the wash are a bit surprising.

First, the d-c Josephson effect is simply that electron pairs <u>can</u> tunnel across the barrier and that, in fact, this pair current sees <u>no</u> resistance in the barrier. In other words we can have supercurrent going through this resistive region even when there is zero applied voltage. If you push this too far the electron pairs break up and you have normal current flowing at a finite voltage. The maximum supercurrent I_M is typically on the order of microamps.

Josephson predicted this zero voltage tunneling current in 1961 and derived the equation

$$I_S\big|_{V=0} = I_M \sin\varphi \qquad (1)$$

where φ is the quantum phase difference between the electron pairs on the left and on the right-hand sides of the insulating layer in Fig. 9a. There are subtle but very basic coherence properties in a superconductor described by a complex order parameter $\psi \propto e^{i\varphi}$. All electron pairs in the entire right-hand sample have the same phase φ_R and all those on the left again have a common phase φ_L. The φ in Josephson's formula is the difference in the phases on the right and on the left.

The quantum phase coherence is tricky to understand and the Josephson equations don't apply rigorously in all cases of interest anyhow, so let's simply go on to the list in Fig. 10 of the various types of junctions and weak links that have been used.

The tunnel junction investigated by Josephson is made with two cross strips of superconducting film evaporated on a substrate, usually glass. The oxide layer is in between the superconductors where they cross. Any kind of weak link will do, however. For all practical purposes two wires pressed together or a sharp point touching another superconductor acts like a tunnel junction. A small supercurrent can flow at zero voltage through the contact. The same is true of the Dayem bridge and proximity effect weak links. We already saw a Dayem bridge in the magnetometer of Fig. 7. It's just a thin film with a constriction in it. You can also weaken a localized section in a thin film strip of superconductor by putting normal metal on top of it. The proximity of the unpaired normal electrons weakens the superconductivity at that point. Similarly, impurities can be used to weaken a region of the superconductor.

The Clark SLUG is an interesting case. It's just a blob of solder on a niobium wire. Superconducting weak links form where the insulation is bad. As simple as these things are, it turns out that the Clark SLUGS can also be used as sensitive instruments such as the femptovoltmeter.

THE A-C JOSEPHSON EFFECT

The second Josephson equation,

$$\frac{d\varphi}{dt} = \frac{2e}{h} V(t) \quad , \tag{2}$$

relates the phase difference to the voltage across the junction, while a separate equation known previously in the derivation of flux quantization,

$$\vec{\nabla}\varphi = \frac{2e}{\hbar c} \vec{A} + \frac{2e\lambda^2}{4\pi^2 \hbar c^2} \vec{J} \quad , \tag{3}$$

relates the phase difference to magnetic fields and to currents. We already saw with Eq. (1) that with a fixed phase difference a d-c supercurrent flows across the junction. This is the case of $V(t) = 0$ in Eq. (2). Now, suppose the applied voltage is a non-zero constant, V. Then Eq. (2) says that φ must increase linearly in time, Eq. (1) becoming

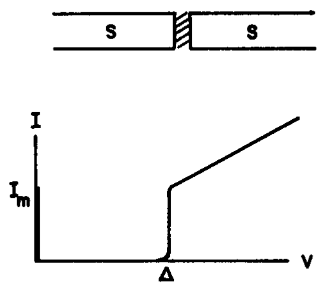

Figure 9. Josephson junction.

9a. Junction formed by a thin insulating layer between two superconductors.

9b. The I-V characteristic.

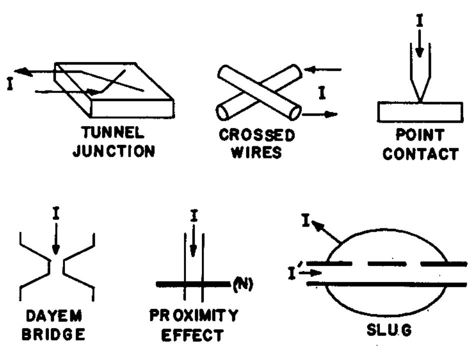

Figure 10.
The various types of superconducting junctions.

$$I_s = I_m \sin 2\pi ft$$

with

$$f = \frac{2e}{h} V .$$

The a-c Josephson effect is the fact that an applied d-c voltage gives rise to an oscillatory supercurrent, the frequency of the oscillation being proportional to the applied voltage. This oscillatory supercurrent does not show up in the I-V characteristic of Fig. 9. When measuring d-c one sees only the normal current of unpaired electrons flowing at the voltage V.

One way to discern that there actually is an oscillating supercurrent is to look for radiation coming out of the junction. This has been done and the oscillating supercurrent due to a fixed applied voltage is actually there.

If you turn that around and apply radiation to the junction, V(t) in Eq. (2) will be a constant plus an oscillatory sine function. Putting that into Eq. (1) gives the sine of a sine function, which means we need a messy Bessel-function expansion. To make a long story short Josephson junctions make sensitive infrared detectors. We will hear more about that later in Dr. Shapiro's talk.

The general topics we have covered are zero resistance, electron pairing due to "virtual phonon exchange," the Meissner effect, type I and type II superconductivity, flux quantization, electron tunneling and the d-c and a-c Josephson effects. The practical large-scale applications of superconductors, the so-called macro-superconductivity of magnet coils, utilize simply the nearly zero resistance of type II superconductors. For in the mixed state below H_{C2} where flux lines penetrate the sample, it is necessary to have good pinning centers to cut down on flux-creep losses in type II superconducting wire. NbZr and Nb_3Sn in particular are being used quite successfully to make powerful magnets, and large-scale motors and generators are under development.

Micro-superconductor applications are the Josephson-junction devices - the highly sensitive IR detectors, magnetometers and volt-meters. Later in the conference we will be hearing about potential Naval applications of these devices, especially the superconducting magnetometers.

SUPERCONDUCTING MATERIALS:

PROCESSING AND PROPERTIES

by
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This section will deal mainly with the high critical field, high critical current density, high critical temperature superconductors, the ones most likely to be used in big magnets, motors, generators, and some of them, to a limited extent, in radio frequency devices and tunneling devices as well.

You have the body centered cubic solid solution superconductors consisting of alloys of group IV and group V elements of the periodic table, (see Fig. 1) group IV and group VI elements, and of group VI and group VII elements. The transition temperatures typically can range up to about 12.5 K (molybdenum-rhenium). The β-tungsten compounds can extend your transition temperatures up to 20.5° (niobium-aluminum-germanium). Typically, the other β-tungsten transition temperatures will run between 14° and 18°, depending on the compound and on how the compound is made. The rock salt structure superconductors have transition temperatures in about the same range -- 14° to 18° -- and there the highest transition temperature also belongs to a pseudo-binary compound - a mixture of niobium nitride and carbide. (1)

Since it is fairly easy to visualize the body centered cubic crystal structure and the rock salt crystal structure, Fig. 2 shows only the beta tungsten structure. Schematically, the formula for beta tungsten structure is A_3B: Nb_3Al, V_3Si, V_3Ga, Nb_3Sn, etc. The "B" atoms occupy the corners of the cube and the center (the center atom is hidden in Fig. 2) and the "A" atoms occupy chains: three perpendicular chains of A atoms, niobiums or vanadiums or others, really wedged into tetrahedral sites in the "B" lattice, and consequently rather highly distorted.

Certain crystal structures favor superconductivity, and as a matter

Fig. 1: A table of the principal high temperature, high-field superconductors, with critical temperatures.

BODY - CENTERED CUBIC SOLID SOLUTIONS
(T_c up to 12.5°)

IV - V	IV - VI	VI - VII
Ti-Nb (to 9.8°) (1)	Ti-Mo (to 4.25°) (3)	Mo-Re (to 11.1°) (5)
Zr-Nb (to10.8°) (1)		W-Re (to 5°) (1)
Ti-V (to7.5°) (1)		
Ti-Ta (to 9.05°) (2)		
Zr-V (to 5.9°) (4)		
Hf-Nb (to 9.6°) (1)		
Hf-Ta (to 6.5°) (1)		

BETA TUNGSTEN STRUCTURE	ROCK SALT STRUCTURE
Nb_3Sn (18.0°) (6)	NbN (16.8°) (11)
Nb_3Al (18.8°) (7)	NbC (10.5°) (12)
$Nb_3Al_{.8}Ge_{.2}$ (20.5°) (8)	NbN-NbC solutions (up to 17.9°)(13)
V_3Ga (14.5°) (9)	
V_3Si (17.0°) (10)	

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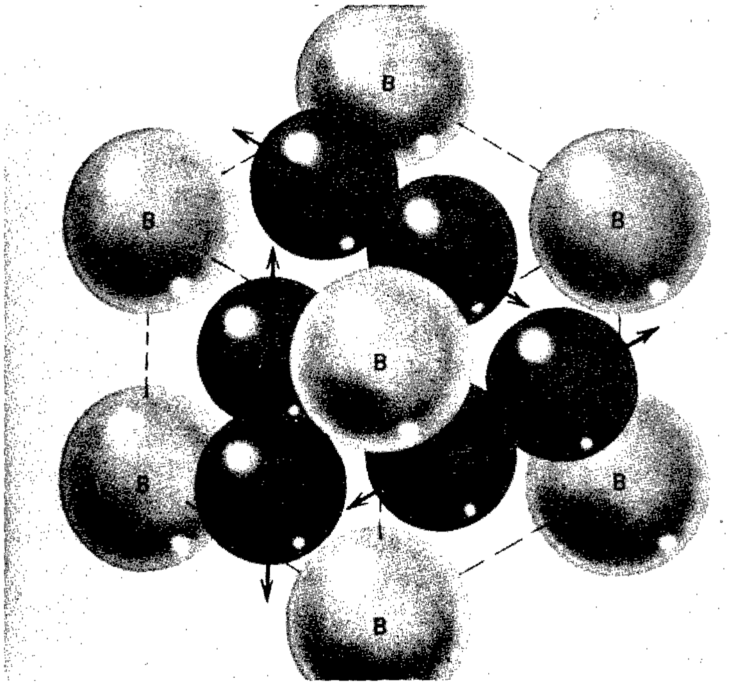


Fig. 2

A schematic drawing of the beta tungsten unit cell, containing six "A" atoms and two "B" atoms (one at the center). From The Structure and Properties of Materials Vol IV: Electronic Properties, by R. M. Rose, L. A. Shepard and J. Wulff (Wiley, New York, 1966).

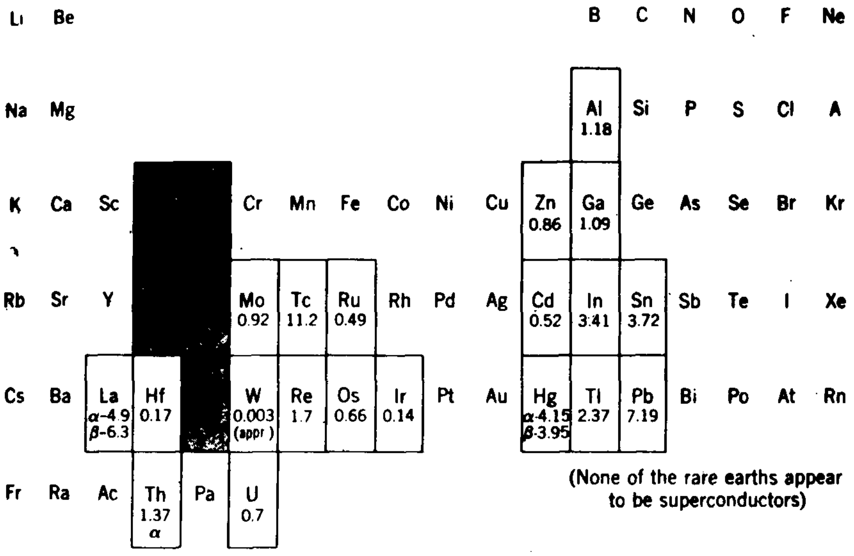


Fig. 3

The occurrence of superconductivity in the periodic table. From The Structure and Properties of Materials Vol IV: Electronic Properties, by R. M. Rose, L. A. Shepard and J. Wulff (Wiley, New York, 1966).

of fact, as Matthias pointed out some years ago (2), an examination of the superconducting elements on the periodic table will show that there is systematic behavior again. Fig. 3 shows that the highest transition temperatures are in groups V and VII of the transition series (incidentally, the transition temperature for technetium in this figure is out of date . It should be closer to 8.5°). These empirical rules are an effective "guide to the perplexed" when searching for high transition temperature superconductors, particularly as extended by Matthias (2). The essential idea is to plot transition temperature versus average electron-to-atom ratio, for compounds and alloys as well as pure elements. The electron-to-atom ratio is taken in a very naive way: just average the column numbers in the periodic table for the alloy or compound. You then get a big peak at about 4 3/4 and you get another big one at about 6 3/4, as Fig.4 (Matthias' original diagram) shows. You will find that just about every useful superconductor we have has effective electron-to-atom ratios near those numbers. For molybdenum-titanium alloys, for instance, which particular composition will have the highest T_c? We should aim for 6 1/2 - 6 3/4 or 4 3/4. Since titanium is in group IV and molybdenum is in group VI the magic number is 4 1/2 - 4 3/4 and this corresponds to 10 - 15% molybdenum and the rest titanium; indeed, the highest T_c falls in this range of compositions. Fig. 5 deals with a case having more practical interest, the Nb-Ti alloy system, and shows transition temperature versus composition. There is a peak somewhere between 20 and 40 atomic % titanium which corresponds to an electron-to-atom ratio between 4.6 and 4.8.

Although the empirical situation is, as you can see, straightforward, theoretical explanation of such behavior is not. Dr. Takken has given you the BCS (3) formula for the superconducting to normal transition temperature: $k_B T_c \simeq 1.14\ K\omega_g \exp(-1/N(0)V)$; $K\omega_g$ is a cut-off energy for the electron-phonon interaction, N(0) is the density of states at the Fermi surface and V is the electron-phonon-electron interaction. You then can increase the density of states, increase the cut-off energy, or you can increase the electron phonon interaction, to increase T_c. A good way is by making a softer, more unstable, more easily polarizable material, as Dr. Takken told you.

It is tempting to explain Matthias' plot with those two sharp peaks in the transition metals, as the variation of density of states across the transition series. However, an equally good argument could be made for the electron phonon interaction. I don't know what to think at this point. Consider the atomic chains in the beta tungsten lattice -- those three orthogonal chains of niobium or vanadium atoms -- they are really squeezed together, and rather distorted. There might be a very huge and a very anisotropic density of states; on the other hand, the effect on the phonon spectrum is also remarkable. One thing is certain, if you disrupt those chains in any way, if you pull out a few atoms, say every tenth atom out of those chains of niobiums or vanadiums, your T_c will go completely to pot. Avoidanee of such disorder is the general underlying principal behind the heat treatment

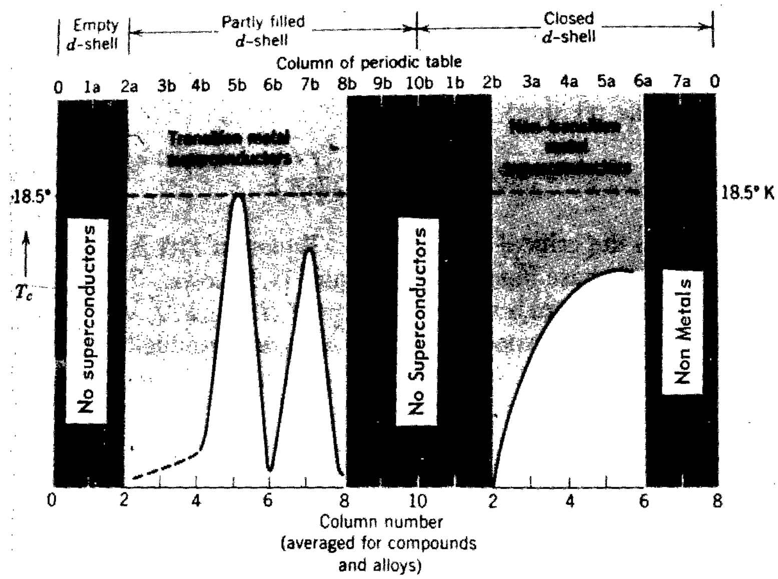


Fig. 4 The variation of T_c with position in the periodic table. (From B. T. Matthias, *Progress in Low Temperature Physics*, Vol. II, p. 138, ed. by C. J. Gorter, North Holland Publishing Co., Amsterdam, 1957.)

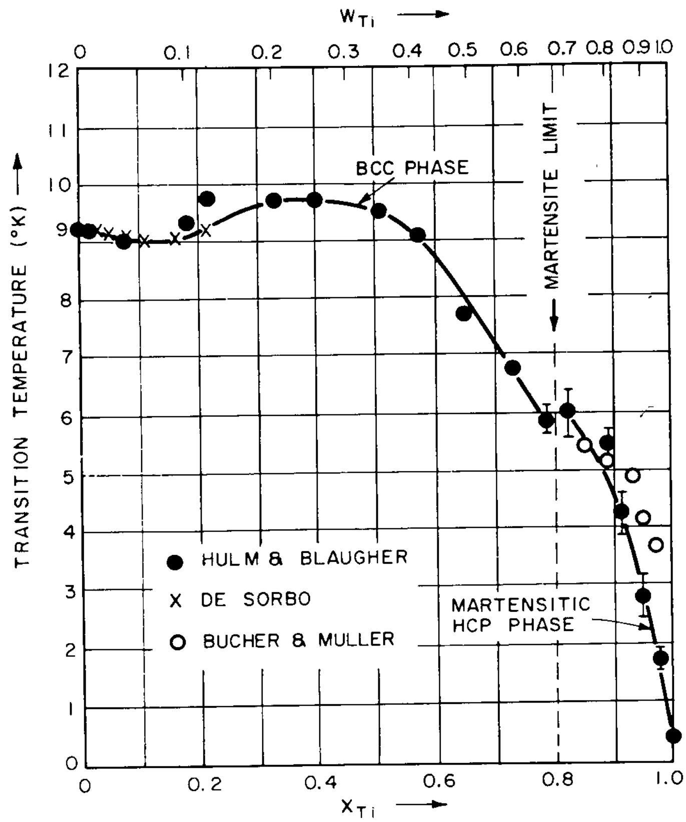


Fig. 5

The variation of T_c with composition for Nb-Ti alloys. From J. K. Hulm and R. D. Blangher, Phys. Rev. 123, 1569 (1961); W. De Sorbo, Phys. Rev. A140, 914 (1965); E. Bucher and J. Muller, Helv. Phys. Acta 34, 410 (1961).

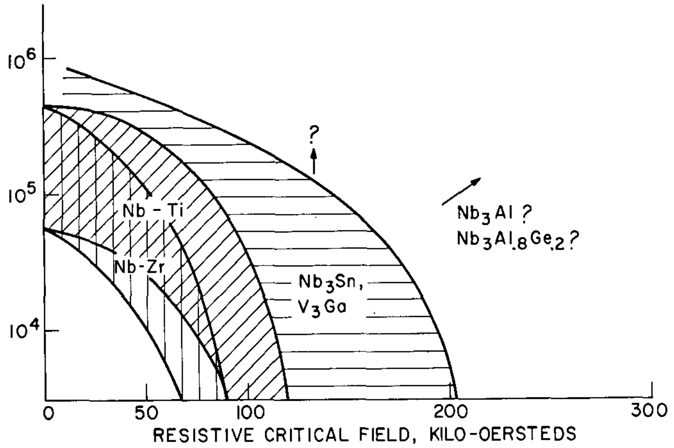


Fig. 6

Approximate ranges of J_c vs. H at 4.2°K for commercially (or nearly so) available high-field superconductors.

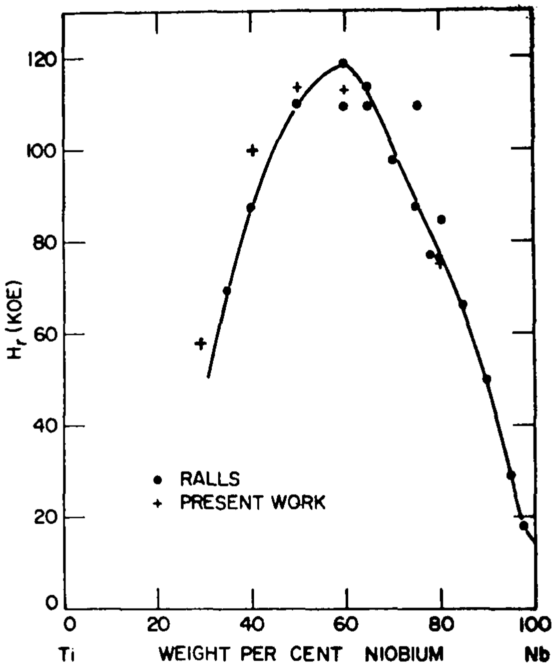


Fig. 7

Resistive critical field vs. Composition for Nb-Ti alloys. Courtesy of K. M. Ralls.

of the beta tungsten compounds to attain maximum transition temperature.

Now let's compare the properties of superconductors which can be used for high current, high field, high temperature applications, for use in solenoids, dipole magnets, quadrupole magnets, motors, generators and the like. Typical plots of critical current density (J_c) versus applied field (H) appear in Fig. 6. For the current range 10^4 to 10^6 amps/cm^2, we can gain an intuitive feeling for such numbers if we calculate that a critical current density of 10^5 amps/cm^2 corresponds to passing up to 50 amperes with no measurable resistance through any length of 0.010" dia. wire we please (subject to a few instabilities).

Typically, the rock salt superconductors and the beta tungsten superconductors have about the same capability given optimum processing. The solid solution superconductors, say titanium-niobium, (which dominates the commercial scene just now) will have smaller critical current densities and zirconium-niobium,(which is largely obsolete now), appears as shown in the figure crossing over Ti-Nb, and finally, by way of comparison, pure elemental niobium is somewhere down near the origin, unless it is severely deformed. Although we recently found that deformed Nb can remain superconducting up to about 50 - 60 kG· (4), I'm not going to discuss Nb because high fields and current densities come more easily with the alloys. However, it is quite useful in radio frequency circuits and tunneling devices.

The J_c vs. H curves are very sensitive to the way you prepare the superconductors, and the composition. Fig. 7 shows critical fields as a function of composition for Nb-Ti alloys. Actually, the peak in critical field doesn't necessarily come at the same composition as the peak in critical temperature. For instance, look at Fig. 8; these are typical J_c verses H curves for various cold-worked niobium-zirconium alloys. You can see that about 50 - 50 Nb-Zr is probably your best composition from the point of view of critical field; when this alloy is subjected to about 90 kilogauss at 4.2°K your critical current density drops sharply to a very unusable value, so that 90 k-gauss is the "resistive critical field" of this particular alloy. However, the highest transition temperature in the Nb-Zr system belongs to the 25% Zr alloy, for which the resistive critical field is only about 70 k-gauss.

The primary consideration in determining the resistive critical field is the "upper critical field" H_{c_2} of Ginzburg and Landau (5):

$$H_{c_2} = \sqrt{2}\, \kappa\, H_c$$

All the superconductors I have mentioned are of the second kind with very large κ. For Type II superconductors H_c is defined by the difference in free energy between the super electrons and normal electrons per unit volume.

$$\frac{H_c^{\ 2}}{8\pi} \equiv \Delta G_{n \to s}\Big|_{H = 0}$$

To raise H_{c2}, we raise κ. Gor'kov and Goodman (6) found a good approximation for kappa, that

$$\kappa \simeq \kappa_0 + \kappa_\ell$$

The term κ_0 is due to the pure material, and κ_ℓ is due to alloying, and in fact

$$\kappa_\ell = 7.5 \times 10^3 \sqrt{\gamma}\, \rho \quad ,$$

where γ is the electronic specific heat coefficient (cgs) and ρ is the resistivity (in ohm - cm) of the normal state.

Since high κ means high H_{c2} and high critical field, you should push your resistivity ρ up as far as you can. This is typical of the body centered cubic solid solution alloys, such as Nb-Ti alloys. The resistivity ratio (ρ_{300} / $\rho_{4.2}$) of these alloys is typically around one. As a matter of fact, some years ago Ken Ralls (7) found a few where the resistivity ratio was less than one. Kappa is of the order of 10 or 100 in most of these really useful superconductors. I would be cautious in identifying the resistive critical field completely with H_{c2} because there are complicating factors that come in, such as paramagnetism in the normal and mixed states (8), and possible "internal surface" effects as well (9). The latter is simply the possibility of surface nucleation <u>inside</u> the superconductor, analogous to the "external surface" nucleation at H_{c3} which was discussed in the previous paper. However, I can tell you that a very high kappa will result in a high resistive critical field, even if the two are not necessarily identical.

Now to get down to business, i.e. "How do you make these things?" The beta tungsten superconductors are quite brittle. I think the first β tungsten superconductors were made experimentally by arc-melting. The result is a rather brittle button that will crumble into a powder with any persuasion. The first usable β tungsten superconductor was made at Bell Labs (10). It was based on Nb_3Sn; the idea was to take some mixed Nb and Sn powders and put the mixture inside a niobium tube and then draw the whole thing down to compress the powder inside, resulting in a fine wire core of the mixed powder. Then the solenoid is wound and after the magnet is wound the whole thing is heat treated, so the center of the wire reacts to form Nb_3Sn. There are problems attached to this procedure. In the first place, getting a really uniform core from a powder misture is hard to do on a production basis. Second, finding an insulation which will stand up under the heat treatment temperature (which happens to be 900°C) without disintegrating is no mean feat. It was in the end easier to make Nb_3Sn - containing wire that was flexible enough so that you could make the

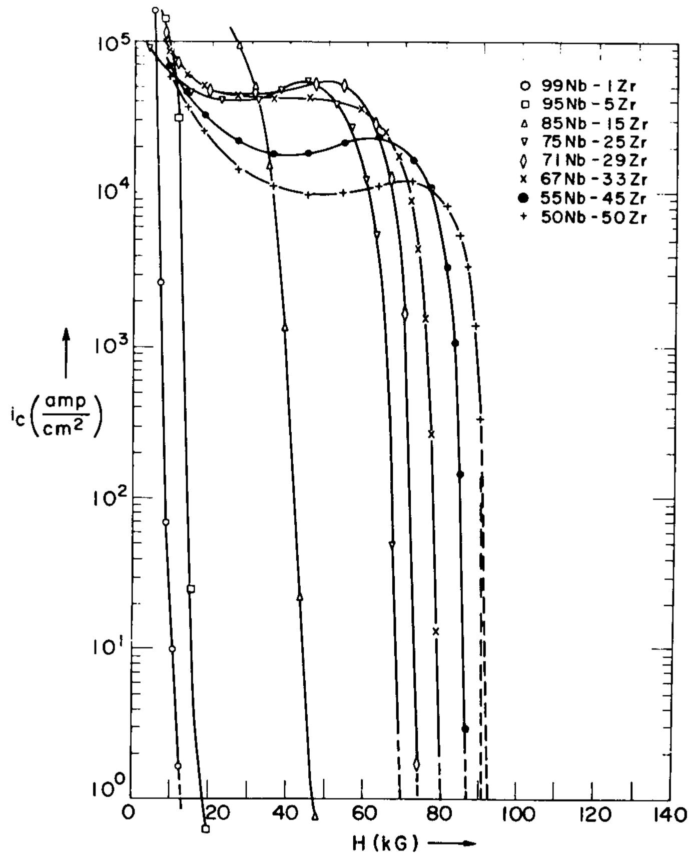


Fig. 8 J_c vs. H data for various Nb-Zr alloys at 4.2°K. Courtesy of K. M. Ralls.

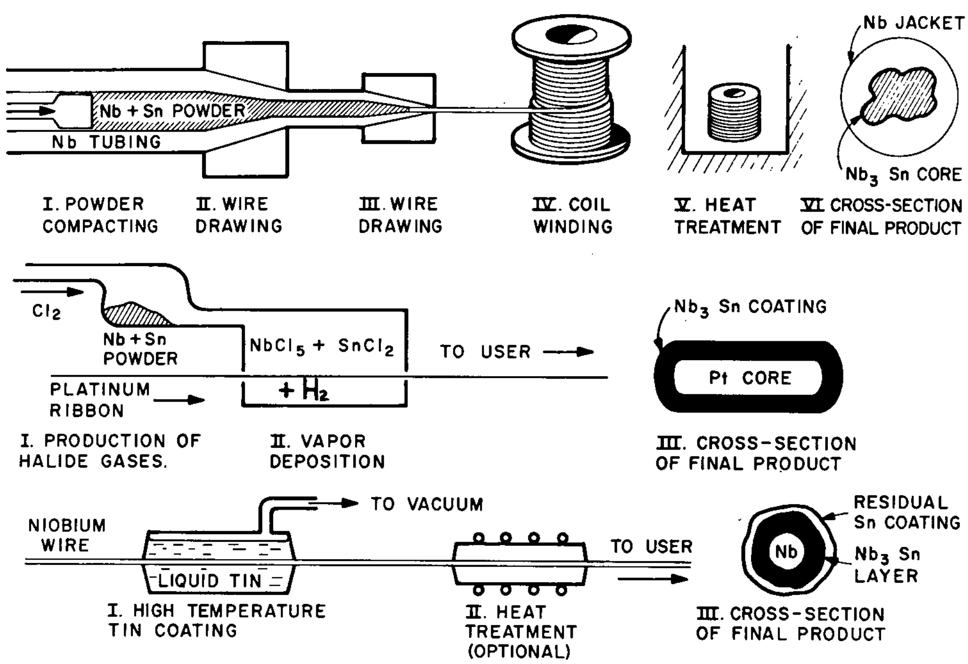


Fig. 9

Schematics for various fabrication methods for Nb_3Sn wire or ribbon.

the niobium tin first and then wind the magnet. This can be done in a number of ways. Fig. 9 shows several, including the Bell technique and also the RCA technique (11), in which the mixed halides are reduced with H_2 on a hot substrate. The result is a deposit of Nb_3Sn and a halogen acid, usually HCl. This ferocious mixture is cut with a carrier gas, usually helium. The substrate can be anything that can stand up to the temperature and won't deteriorate. Various high temperature alloys, Hastelloys, platinum (if you have the money), quartz and others have been used.

Another way is simply to take niobium ribbon and dip it in a tin bath, coating it with tin, and then heating it up to about 900°C, which is again the optimum temperature. A reaction layer of Nb_3Sn and maybe a little bit of excess tin on the outside is the result. The essential idea is to make a ribbon with a very thin layer of Nb_3Sn which will bend. Ideally, the Nb_3Sn should be at the center of the ribbon at the neutral axis where it would never get any stress from bending.

Ribbon of Nb_3Sn has also been made by co-evaporating niobium and tin in vacuum onto a hot substrate. Stoichiometry is controlled by control of evaporation rates, and that is the difficult part of the co-evaporation technique. Also, the two components may be co-sputtered, or the compound made by pressing a powder or by arc-melting, and the compound sputtered. Niobium nitride and the rock salt superconductors are very effectively made up by sputtering in reactive gas, and in fact the data I gave you of niobium nitride in Fig. 6 were the results of specimens made at Westinghouse by reactive sputtering (12). In this case niobium was sputtered in an inert gas atmosphere with a little dose of nitrogen and the result was a niobium nitride film which had properties every bit as good as Nb_3Sn (12).

In contrast to the problems in making the intermetallic compounds, the body centered cubic solid solution technology is much easier and much more highly developed, and actually the only superconductor sold in large quantities today is niobium-titanium. The alloy is made by arc-melting or electron beam melting. Titanium sponge is mixed with niobium metal, and melted. The ingot is then forged, extruded, rod rolled, swaged, drawn, or otherwise mercilessly treated until fine wire results. In general the level of J_c will be low unless you have a relatively high titanium alloy, and dissolved oxygen is also essential. It is possible to make a relatively "clean" alloy from crystal bar titanium and electron beam melted niobium; the result will be very high ductility and uselessly low J_c. Some dirt is needed, for instance the addition of about 2000 parts per million of oxygen. Then the alloy should be heat treated at about 350° to 400°. The effect of heat treatment is shown in Fig. 10. The wire used to obtain the data in Fig. 10 came from small laboratory ingots, and the J_c level is below the capabilities of commercial material. Notice that the 300°C heat treatment raises J_c at 40 kilogauss by a factor of six or seven, and 400 - 500°C do even better. Also the 500° heat treatment makes a

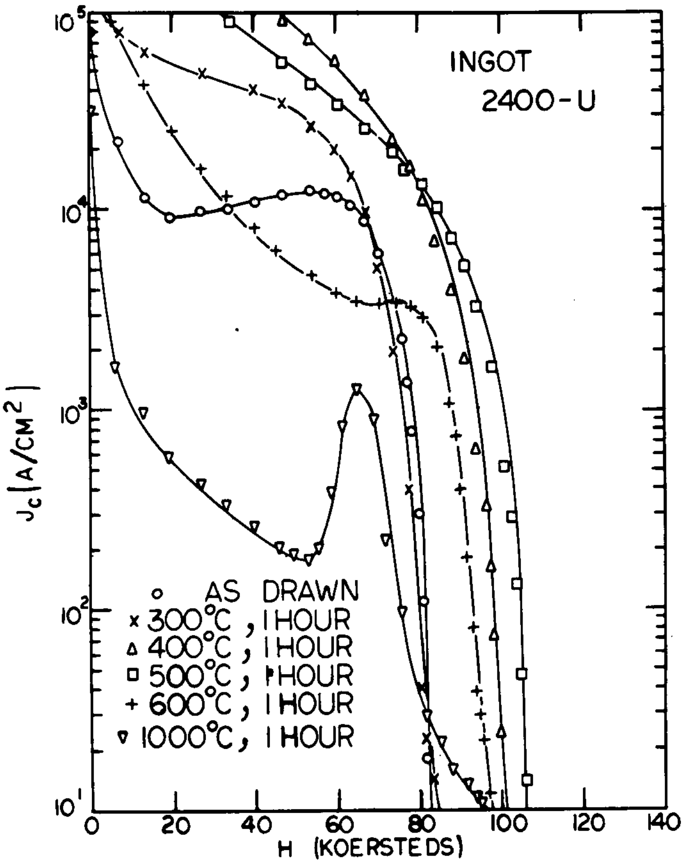
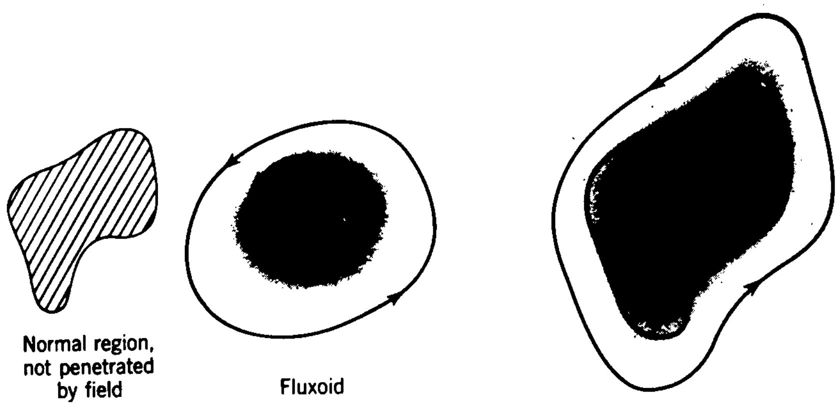


Fig. 10
The effect of heat treatment temperature on the performance of a 60% Ti- 40% Nb alloy wire with 2400 parts per million (by weight) of O_2.

Courtesy of R. L. Ricketts.



(*a*) Fluxoid is attracted to normal region which is not penetrated by the field

(*b*) Fluxoid sits in normal region. lowering free energy of the super conductor

Fig. 11

Pinning by a hole or inclusion: superposition puts more electrons into the superconducting state with no change in magnetic penetration. From The Structure and Properties of Materials Vol IV: Electronic Properties, by R. M. Rose, L. A. Shepard and J. Wulff (Wiley, New York, 1966).

difference of 20 kilogauss in your critical field as well as a tremendous difference in the current carrying capacity.

The increases in J_c shown in Fig. 10 are due to the pinning of fluxons. As the previous paper notes, the fluxons will move when you apply a current, due to the Lorentz force of the current and the applied field. The flux motion causes a voltage, really a Faraday's law voltage parallel to the current and therefore a dissipation of power. To avoid such losses, the fluxons must be pinned in place. The mechanism for pinning is illustrated in a very simple minded way in Fig. 11. The superconductor would really very much like to be both superconducting and as completely penetrated as possible by the magnetic field. (Both of these things will lower the free energy.) The fluxon has a normal spot at the middle of it and if there is an inclusion, hole, or any region which is also normal the number of super electrons will be maximized with no change in penetration by the field by condensing these two normal regions into one. Thus the fluxon is stuck right on top of the heterogeneity - it can be a precipitate particle - it can be a piece of dirt - it can be an inclusion of any kind - it can even be a hole or it can be a groove on the surface (13). When the Nb-Ti alloys are heat treated properly, precipitates result. The precipitates are either the omega (ω) or alpha (α) phases beloved of titanium metallurgists depending on the alloy or depending on the heat treatment temperature. In Fig. 12 the critical current density at about 1/2 of the resistive critical field for a 50-50 niobium titanium alloy (roughly 50 kilogauss) is shown as a function of heat treatment temperature. Thus we are talking about an order of magnitude in J_c, or equivalently the ability, say, of a wire to carry 10 amps or 100 amps before it goes normal, which can make the difference between being unusable and being very usable.

Why, incidentally, do higher oxygen and titanium levels lead to high critical current density? The Nb-Ti phase diagram (14) as well as the present state of our knowledge of metastable Nb-Ti phases show the way to the answer: higher Ti content means more α and more ω (omega) phase, and dissolved oxygen is an α stabilizer (15). Such precipitates, particularly in combination with heavy cold work, will put piles of fluxon pinners into such alloys. These circumstances are very nice, except that high current densities in such alloys are intrinsically unstable. The instability comes from the fact that a very high current density means very high gradients in the magnetic field, since from Maxwell's Laws J is proportional to $\nabla \times H$. So the density of fluxons has a high gradient. Now suppose you move a few of these fluxons, changing that field gradient a little bit; since fluxons repel each other, the field gradient is also a pressure gradient, and, with only the pinners holding back a potential "avalanche" of fluxons, minor readjustments are quite likely. The flux motion however, induces an electromotive force. Remember that you have normal spots at the center of the fluxons and also an inhomogeneous alloy, so you're going to get heating from that EMF. But the heating

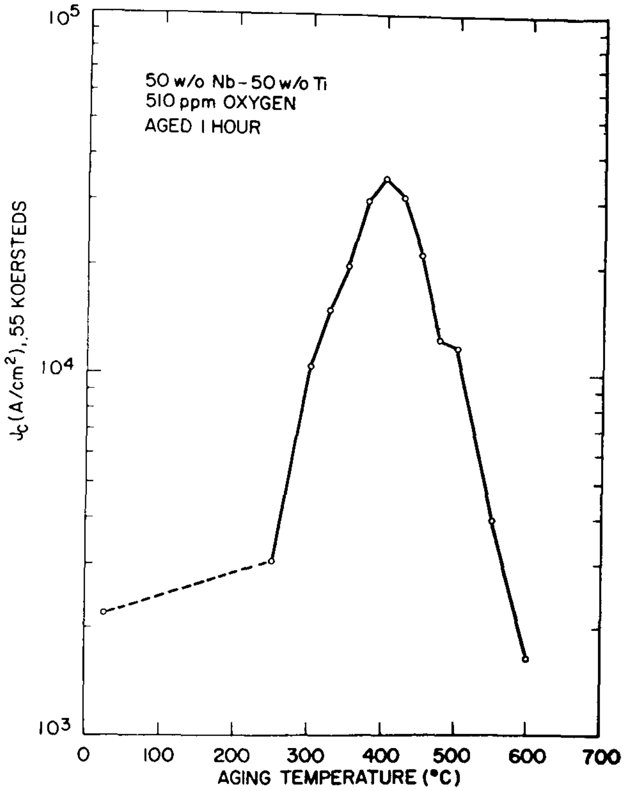


Fig. 12

The effect of heat treatment temperature on the J_c of a 50-50 Nb-Ti alloy with 510 parts per million oxygen. Courtesy of G.C. Rauch, from Trans. Met. Soc. AIME 242, 2263, (1968) by G.C.Rauch, T.H.Courtney and J.Wulff.

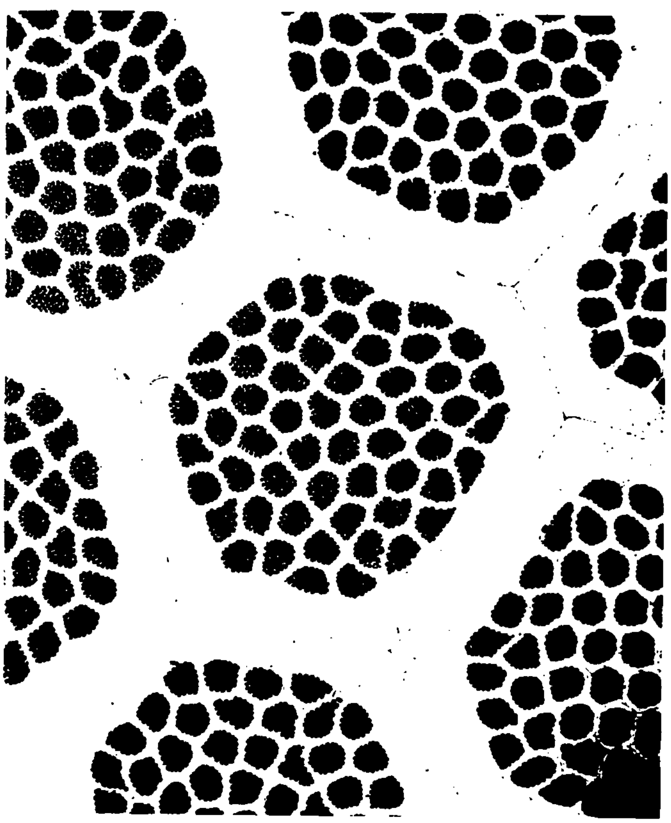


Fig. 13

A copper-Nb composite. Courtesy of H.E.Cline from Trans. ASM 59 133 (1966) by H. E. Cline, B. P. Strauss, R. M. Rose, and J. Wulff.

will weaken the pinning. Once the heating weakens the pinning, some more flux is going to move in; but the additional flux motion gives you more heating so you have an instability that feeds on itself. This problem frustrated the early superconducting solenoid builders greatly, since the long lengths of wire involved, together with limited cooling capability , made the instability very likely. The testing of short samples proved to be cruelly deceptive, as the critical current densities obtained in such tests exceeded the capability of the wound magnet by a large factor.

The magnetic field can move through such superconductors very fast, and heat moves through superconductors very slowly. This is so because high-field, high-κ superconductors are very poor normal conductors, say, compared to copper, which is not a superconductor at all. Niobium titanium alloys at 4.2°K have about 10,000 times the resistivity of OFHC copper when they are normal. With very small eddy currents to retard the motion of the magnetic field, there is a very high diffusivity for magnetic flux through the superconductor. However, the heat created by the eddy currents can't get out so fast because superconductors are very poor thermal conductors.

The instability headache, just like the television commercials say, can be cured three ways. One way is to find a way to bleed off the heat. Another way is to find a way to retard the motion of the magnetic field. The third way is to make a superconductor that is so fine that you will never be able to generate enough of a heat pulse to get the instability going in the first place. One way to begin is to put the superconductor in a normal matrix of something like copper. Copper has a very high thermal conductivity compared to niobium-titanium in the normal state. It has a very low magnetic diffusivity because it has such a high conductivity. Before the stability problem was well understood, it was noticed that copper plating the superconductor helped, but copperplating metals as reactive as Nb-Ti alloys is almost impossible in ordinary aqueous media. From these early samples, often the copper can be peeled off with the fingernail. On the other hand, if a metallurgical bond is formed by laying the wire down on a strip of copper and putting another copper strip on top, and rolling it, then the oxide layer on the surface of the superconducting wire is broken, and you will then find that you have actually stabilized the wire, at least partially. An alternate method is to make a cable, and impregnate the cable with something like indium solder. The most important way is based on an old experimental technique, which was actually first used to make cigarette lighter flints, subsequently used at IBM to study proximity effects on aluminum and lead. The reductio ad absurdum for the technique was done at M.I.T. where we managed to get something like ten million niobium filaments in a 0.006" dia. copper wire (16). Each of these niobium filaments was 100 A in diameter, as verified under the electron microscope. A cross section of the wire before it was reduced to this size is shown in Fig. 13. The way we did this was to put the niobium

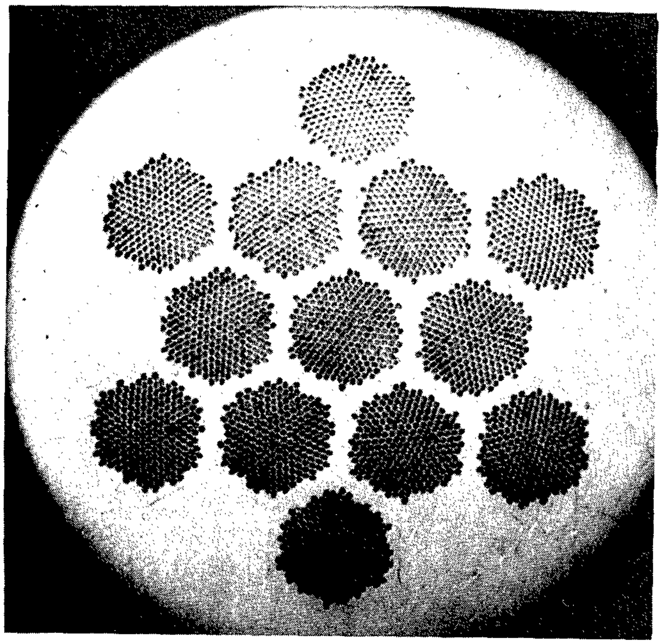


Fig. 14

A copper- (Nb-Ti alloy) composite, produced by methods similar to those of Ref. 16, but on a larger scale. Courtesy P. R. Critchlow and E. Gregory.

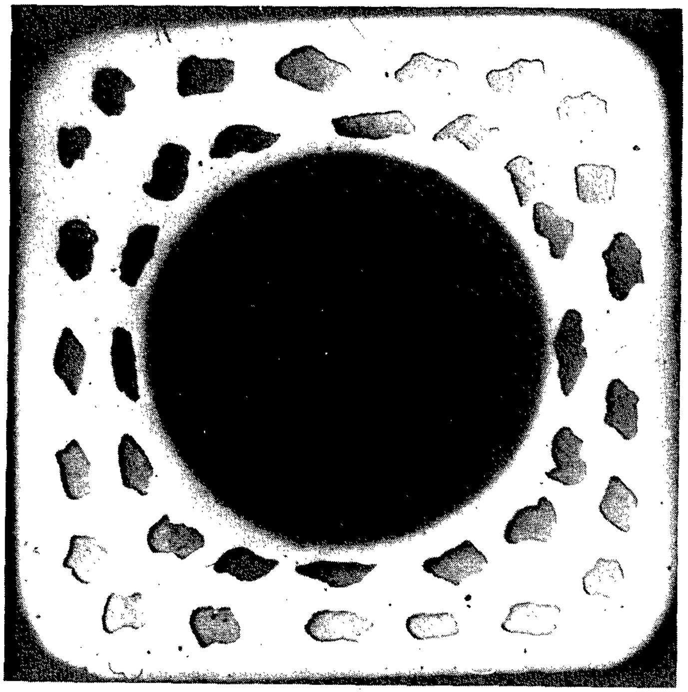


Fig. 15

A hollow copper - (Nb-Ti alloy) composite, to utilize high efficiency cooling techniques. Courtesy P. R. Critchlow and E. Gregory.

in a copper tube and draw it into wire, cut the wire up into 56 odd pieces, stuff it inside another copper tube, draw that down into wire, cut that into 56 pieces, stuff it into another tube and draw that . . . and repeat this five times. In Fig. 13 the families of filaments and also the families of families are shown; the filaments at this point were about 2 μ dia.

Why do you want to make it so fine? Simply because the diffusion equation tells you that for the diffusion of anything, magnetic fields, heat, anything else, the time constant for diffusion out of a slab goes as L^2/D where L is half the thickness of the slab (or wire). Thus the time constant is reduced very effectively for diffusion by reducing the size. Now the diffusion constant for magnetic fields goes as $1/\rho$ (ρ is the electrical resistivity) and the thermal diffusion constant goes as the thermal conductivity over the specific heat. For example, in the case of diffusion of magnetic field through a slab of normal niobium titanium 2 cm. in thickness, the time constant is 50 microseconds. Were the slab copper, the time constant would be 10,000 times as large - half a second. So the composite material should be designed to get the heat out of those filaments at least as fast as the flux is moving out. It turns out, for instance that the flux diffusion constant of OHFC copper is about the same as the heat diffusion constant of normal niobium-titanium, so you can make a composite with a fairly fine geometry with equal parts of niobium-titanium alloy and copper. Consider now an alloy matrix, say cupro-nickel. Cupro-nickel has about 10,000 times the resistivity of OHFC copper and if you look at the L^2/D time constant, it turns out that you have to reduce L by one hundred in order to keep your time constants matched. These crude estimates can be refined; a sufficiently fine filament can be completely stabilized even without the copper (17). Typically, the maximum size for niobium-titanium, with a critical current density of the order of 3×10^5 amps/cm^2, is about 0.003". Various people have worked out reasonable approximations for the critical size, and have come to the same conclusion:

$$d_{crit.} \sim \frac{\sqrt{10^9\, C_p T_o}}{4\, J_c}$$

where C_p is the specific heat, and

$$T_o \equiv \frac{J_c}{\left(-\dfrac{dJ_c}{dT}\right)}$$

Commercially available composites are quite sophisticated, as Figs. 14 and 15 show. We can see rods of niobium titanium and a copper matrix and you can see the geometry is very well controlled. Square, rectangular, and hollow shapes have all been made, and made well. However, without the proper precautions these fancy composites will have the same losses and the same instability as solid super-

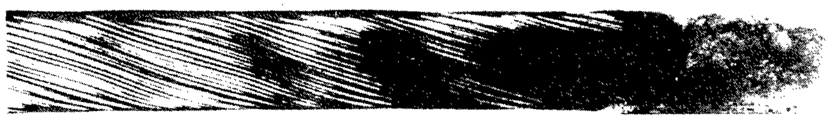


Fig. 16

Braided cable of superconducting composite. Some of the copper has been etched off to reveal the winding. Courtesy P. R. Critchlow and E. Gregory.

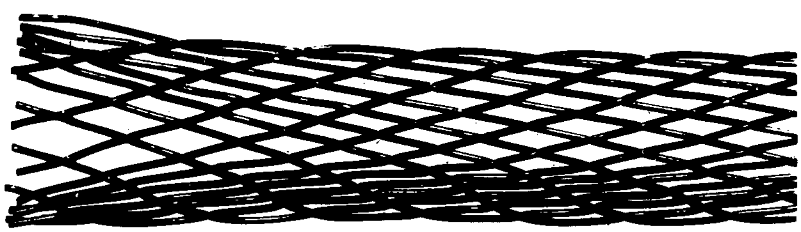


Fig. 17

Completely transposed ("Litz") cable of superconducting composite wire. Courtesy P. R. Critchlow.

conductors. When the magnetic field is applied to superconducting filaments running parallel to each other in the copper matrix, shielding currents will flow, through and between the filaments. As Smith et. al. have pointed out, the shielding currents will cross over through the normal matrix and will be very persistent particularly if the rate of change of the field is high enough (17). In fact, there is a critical length for the crossing of these shielding currents, also found by Smith et. al. (17), who found that essentially all the current in the filaments should cross through the normal matrix if the length is larger than l_c, where

$$l_c \approx \frac{2 \times 10^8 \rho J_c d\lambda}{\dot{H}}$$

(Here, d is the diameter of the filament, $\dot{H}$ is dH/dt and λ a geometrical factor of the order unity.) Now we have trouble. We could even have two completely isolated wires a mile long and if we connect them at the ends we just have a very long effective length ℓ, much longer than the critical length. The solution to this, again pointed out by Smith and the Rutherford group, is to transpose the wires, so that the field does not see parallel superconductors over any length larger than the pitch of the transposition (17). Initially this was done by twisting and there is one problem with twisting which occurs in large composites: when the composite is twisted the field of the current going through the individual filaments tends to overload the outer wires in your composite (18). The self-field effect puts an upper limit on the size of the composite you can make.

To make a large composite to carry very large currents we have to completely transpose everything, by making braided cable or good old fashioned litzwire techniques. Fig. 16 shows braided cable with copper on the outside with the copper partially etched off. Fig. 17 is a "litzwire" that is made up from composites. By way of examples the upper limit on composite diameter with 0.0005" filaments would be roughly 0.050" or possibly as high as 0.010". For larger composites we have to go to something like the litzwire technique. The latter leads us to a number of problems which haven't been really solved yet, such as the mechanical restraint of those wires, e.g. in Fig. 17. If they are allowed to flop all over the place we can expect stability problems again. How to achieve restraint without recoupling the wires and still allow for adequate cooling is a problem.

Notice please that I have avoided discussing ac losses. I know that you would rather build ac motors than dc motors. Most people would-but as you know, the big motors under construction now are homopolar motors - essentially dc machines - or possibly I would guess you could have an ac machine with a superconducting excitation winding. The reason for this is that the ac losses in superconductors such as commercial heat-treated Nb-Ti wire come from the magnetic hysteresis, which is really unacceptably large. Some improvement is possible through the use of fine-filament transposed composites. There may also be ways to make superfine composites with very sophisticated matrixes that sharply reduce eddy current losses. Certainly this area awaits the design of superconducting materials specifically for ac rather than dc applications.

All the composite technology has thus far been referred to the ductile niobium titanium alloys. However, to get well above 100 kilogauss, in large-scale devices, we have the problem of stabilizing niobium tin ribbon, which is a headache. The extruding and forging of copper on top of niobium tin ribbon would break it to pieces. You can leave a bit of tin on the outside of the Nb_3Sn and then copperplate or silverplate, but this turns out to be unsatisfactory for a number of reasons, i.e. limited adherence, conductivity and thickness, and you still can't develop twisted and transposed multifilamentary composites at a reasonable expense with such a conductor. A partial answer has appeared in several places and that is to put niobium in a tin-bronze matrix, or vanadium in a gallium-bronze matrix, develop the desired geometry with the Nb-Ti alloy - copper matrix technology, and then heat treat to form the beta-tungsten compound at the bronze-niobium or bronze-vanadium interface. The problems are that you have a high resistivity matrix and you may have a lot of copper in your beta-tungsten compound.

Another technical problem involved with making the beta-tungsten compounds is temperature. Reaction temperatures range from 600° to 900°C and up; for the case of Nb_3Al the gateway to $Nb_3Al_{.8}Ge_{.2}$ with transition temperatures of 20.5° , much higher reaction temperatures, perhaps 1600 - 1800° are necessary. But for devices to operate at 12 - 14°K, there isn't much choice. Nb_3Al and $Nb_3Al_{.8}Ge_{.2}$ with optimal T_c are now made by arc-melting the components, or a very high temperature anneal, both followed by lower temperature heat treatment. The necessity of high reaction temperatures to attain high T_c is a prime technical headache for the practical fabrication of the really high T_c beta tungsten superconductors.

I have not mentioned radio frequency problems, where Nb is in use. Niobium rf cavities for the X-band that operate with Q above 10^{10} have been made. The technical problems there are mainly connected with ultra high vacuum annealing to get the cleanest possible surface. There are aging effects if these cavities lie around in air at room temperature, and Q goes to pot (especially in Cambridge air). Smoothness of the surface is quite important, and very difficult to attain. Nb is also used for making tunneling devices. For reliability, shelf life and tolerance of abuse, the best tunnel barrier is apparently niobium oxide. Let me give you an example: Margaret MacVicar and I did some tunneling experiments (19) on single crystals of niobium a few years ago and we eventually got our technique to the point where we got 85% yield of good tunneling junctions. Better than that was the fact that we could disconnect all the soldered connections, pull them off, take x-ray Laue diffraction pictures, put the junction in the drawer for six months and then reconnect the connections and reproduce our original tunneling characteristic. It took us two years to learn how to make junctions that way, but at least it's possible and it is one of the few ways I can think of where it is possible to make really reliable tunnel devices. Another possibility is synthetic non-oxide tunneling barriers - amorphous carbon for instance (20, 21) - which would be a very very stable tunneling barrier to make, say, a Josephson device or any sort of device based on tunneling.

So here are my prognostications: I believe phonon softening by structural modification is limited by the fact that, as Dr. Takken pointed out, the structure gets so soft that it becomes unstable. This happens in thin films and it happens in the bulk too. I can't really speculate on organic superconductors, but I can see 30 K in more mundane materials within the next decade. I think much sooner along will be use of aluminum rather than copper as a stabilizing medium in high field superconductors. Simply because commercially available high purity aluminum has a lower residual resistance at 4.2 K than OFHC copper and even more important the magnetoresistance of aluminum saturates, levels off whereas the resistivity of copper keeps going up as you boost the magnetic field. Also, there should be a solution to the ac superconductivity problem. I would like in closing to acknowledge the aid and consideration of many people, including Drs. A. D. McInturff, B. P. Strauss, P. R. Critchlow, E. Gregory, G. C. Rauch, K. M. Ralls, and R. L. Ricketts, all of whom helped make this review more complete and better than it might have been.

Hanrahan, NRL

I would like to ask if you think your stability story explains the so called current degradation.

Professor Rose

Exactly. What is called current degradation or coil degradation is due to thermalmagnetic instability. The very poor thermal diffusivity and very large magnetic diffusivity in the superconductor which cause the instability can be countered by using composites of the sort I have mentioned. In fact it is now possible to attain short sample performance in rather large coils. Besides fully stabilized composites you can make partially stabilized composites if desired.

John Daunt
Stevens Institute of Technology

I want to get to early in your talk, where you were talking about electron-phonon-electron interactions and their effect on this interaction of the phonon spectrum. Have actually any measurements for example by neutron spectroscopy been made of the phonon spectrum of the beta-tungsten material?

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Professor Rose

I don't recall. I think someone is doing niobium now. The phonon spectrum of beta tungsten materials by neutron diffraction, not that I know of.

Sidney Shapiro

As a high temperature superconductor, what about metallic hydrogen?

Professor Rose

For those of you who are not familiar with the metallic hydrogen situation the idea is to put the hydrogen under a lot of pressure and make a hydrogen crystal, and as every elementary course in solid state physics tells you if you hooked all those hydrogens together you would get a band structure and therefore a metal. Now metallic hydrogen having a very easily polarizable lattice ought to be a beautiful superconductor. Actually we are now tackling this at M.I.T.; we are using a new approach to high pressure involving a large number of very strong graduate students!

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CRYOGENIC REFRIGERATORS*

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Abstract

An account is given of recent developments of small and medium scale cryogenic refrigerators suitable for maintaining equipment and devices, and in particular superconducting systems, at very low temperatures. The temperature range that is covered is that below 20K, with emphasis on the liquid helium region (1K to 4K).

The characteristics, modes of operation and performances of existing types of refrigerators are described. A discussion is given of possible future developments and applications.

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Before discussing mechanical cryogenic refrigerators, I wish to say a few words regarding the way in which most experimental work on superconductors has been done in the past, and indeed continues to be done, namely by the use of liquid refrigerants, particularly liquid helium. The temperature ranges of liquid refrigerants are shown in Table I which gives the boiling points and triple points of generally available cryogenic liquids. It is evident that liquid hydrogen gives a range from 20.4K to 14K. Liquid helium (mass 4) has a boiling point of 4.2K. The lowest temperature to which one can conveniently reduce liquid helium is approximately 1K or a little less, so that one has a range of about 4K to 1K. At higher temperatures liquid nitrogen provides a range from about 63K to approximately to 77K.

Many of the properties which one may wish to observe require investigations in the gaps between these ranges of temperature available with cryogenic liquids. This has been one of the reasons for the development of mechanical cryogenic refrigerators. However, there is a simple technique which has been used in the past and which is still used for bridging these temperature gaps. This is illustrated in Fig. 1. In Fig. 1, S is the sample of interest, which one wishes to maintain cold. It is located in a vacuum vessel, V, which in turn is immersed in a bath B of a suitable refrigerant liquid, say liquid helium. The sample is thermally connected to the walls of the vacuum vessel (and hence to the liquid helium bath) by a weak thermal link, L. The sample also has an electrical heater, H and thermometer, T attached to it. By applying the right amount of heat one can maintain the temperature of the sample above that of the bath, up to 20 degrees higher or more. In general one employs a feed-back system in which deviations from the desired temperature are sensed by the thermometer and serve to control the heater and maintain the temperature constant. These systems involving liquid baths have limitations and one of the obvious ones is that it is not very satisfactory for use outside the laboratory, for example, in industrial or in defense applications. Hence, much effort has been made in the last several years in the development of mechanical cryogenic refrigerators, particularly for operation below 20K. It is these which I wish to discuss in the remainder of this paper.

Small scale cryogenic refrigerators capable of providing 1 to 10 watts refrigeration have already been developed by many companies and are quite practical. There remains however some future develop-

Table I
Boiling Points, Triple Points, Critical Temperatures and Inversion Temperatures of Cryogenic Fluids

Substance	Boiling Point °K	Triple Point °K	Critical Temperature °K	Inversion Temperature °K
Helium (He^4)	4.2	–	5.19	50.5
Hydrogen (H_2)	20.4	13.96	33.2	204.6
Nitrogen (N_2)	77.3	63.1	126.0	621
Air (21% O_2)	80.1		132.5	603
Argon (Ar)	87.4	83.9	151.1	723
Oxygen (O_2)	90.1	54.4	154.3	893

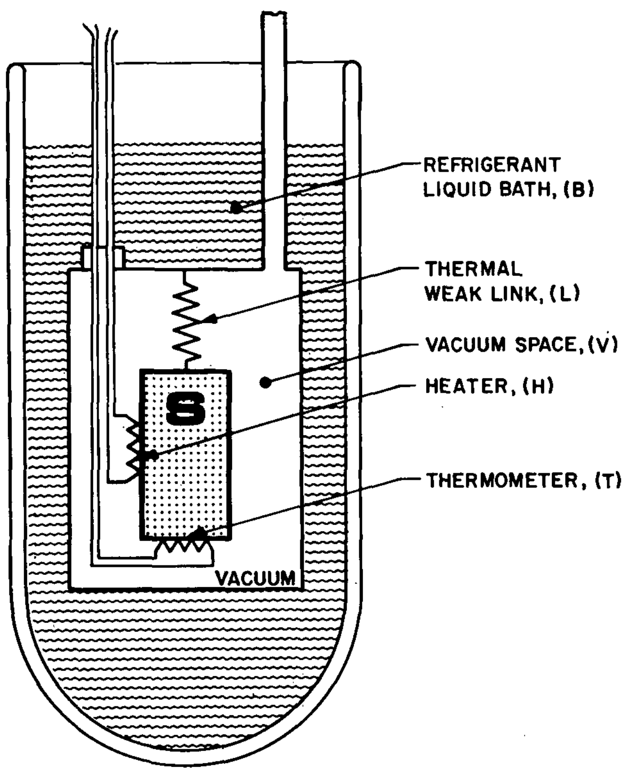

Fig. 1 Diagram of arrangement for maintaining specimens or devices at temperatures other than those available with cryogenic liquids.

mental work, particularly with regard to the question of reliability and also with regard to the question of the interfacing these refrigerators to the devices to which they will be applied. Not so many companies however, provide medium scale cryogenic refrigerators and by medium scale I refer to refrigerators which operate in this low temperature range and provide the order of magnitude a hundred watts of refrigeration. There has been in the last few years a significant development in medium scale refrigeration which I think is of great interest and which I shall mention later.

Large scale refrigeration, of the order of a thousand watts and more of refrigeration at these temperatures, would have to be a custom item. Many large continuous helium liquefiers have been made for liquifying helium at locations near the helium wells, for subsequent distribution of the helium in the liquid form. These large scale systems use turbo-expanders, whereas the medium scale and the small scale systems so far mostly employ reciprocating expanders. Development is in progress on turbo-expanders for medium and small scale refrigerators.

There are many different types of refrigeration cycles which are used for cryogenic refrigerators. Table II gives a partial listing of these. It is not possible to discuss all these in this paper. Instead I shall point out which of the cycles have been developed so far or show promise for the future. The cascaded evaporation system, though highly efficient, is not suitable for temperatures below liquid nitrogen temperatures. The Linde system is used, the Brayton cycle is used, and the Claude cycle is very much used. These are all satisfactory, particularly for medium scale and large scale refrigeration. The Stirling cycle and modifications of it, and the Gifford-McMahon System are successfully used in miniature systems and even for the medium scale systems. Development is proceeding on the Vuilleumier cycle, which shows promise for miniature applications. I think the same thing can be said of the Solvay cycle, which is an old cycle. The other cycles and systems listed in Table II are not being worked on actively for refrigeration below 20K, except for the He^3 Dilution Refrigerator. They are however of interest and, were there more time, they would merit serious discussions, particularly when projecting into the future. Adsorption cooling and the Dilution Refrigerators are powerful systems, but in general only applicable for temperatures below the liquid helium temperature range. I regret to say that there is no time this morning to discuss these systems, but they

Table II

Partial Listing of Thermodynamic Cycles and/or Methods Used in Mechanical Refrigerators or proposed for use in Mechanical Refrigerators

Cascaded Evaporation Systems
Linde Systems (Joule-Thomson Effect)
Brayton Cycle
Claude Systems (Claude-Heylandt, Fränkl, Kapitza)
Stirling Cycle (Ericsson Cycle)
Gifford-McMahon System (Simon Helium Liquefier)
Vuilleumier System (Bush, Taconis)
Solvay Cycle
Pulsed Tube
Ranque Tube (Hilsch)
Magnetic Refrigerators (Daunt, Van Goen)
Roebuck Device
Adsorption Cooling
He^3 Dilution Refrigerator

are valuable systems applicable to the lowest temperature ranges down to 0.01K.

Table III shows some of the features of currently used cycles very briefly and the following commentary is made on the general methods listed in Table III.

Cascaded Evaporation Systems are only applicable down to about liquid nitrogen temperatures. Joule-Thompson Expansion Systems (Isenthalpic expansion) are applicable to all gases provided one starts initially below the inversion temperature. They are mechanically simple but they involve high pressures and they are relatively inefficient. Isentropic Expansion Systems, used for instance in the Claude cycle and the Brayton cycle, are quite generally applicable. They use conveniently low pressures although they are mechanically more complex. They are suitable for medium and large scale operations, particularly in large scale operations using turbo-expanders. Moreover they can be made with high efficiency. The other systems listed, namely modified Stirling cycles and displacement expansion engines, (e.g. Gifford-McMahon systems and Vuilleumier cycles) are quite generally applicable; the pressures involved are low and they are convenient and efficient for small scale operations.

To give some preliminary comparison of the efficiencies of these methods, the following gives data for refrigeration at about 80K. The Stirling and modified Stirling cycles and the Gifford-McMahon Systems show measured efficiencies in the range of 30 to 35 percent of the Carnot efficiency. This is very high efficiency. The Claude and similar Isentropic Expander systems are in the range of 25 to 30 percent of the Carnot efficiency at these temperatures and Joule-Thomson systems are in a range around about 15 percent of the Carnot efficiency.

The Vuilleumier cycle is much discussed nowadays and perhaps it might be interesting to digress a little to show schematically what it is and how it works. Vuilleumier incidentally was a US citizen who lived in the state of New York and he patented this cycle in 1918. It is quite an old cycle therefore but for some reasons it is only recently coming to be of interest. A variety of it was patented by Vannevar Bush in 1938 and another variety of it was patented by Taconis in 1951 and since that time there have been further modifications and extentions which have been patented. Fig. 2 gives a diagram for the system

Table III

General Method	Applicability	Pressures	Comments
Cascaded Evaporation Systems	Only applicable to liquid N temperatures	Low	Mechanically complex. High Efficiency.
Joule-Thompson Expansion Systems	Initial temperature must be below Inversion Temperature	High	Mechanically simple. Relatively low Efficiency.
Isentropic Expansion Systems	Generally Applicable	Low	Mechanically complex. High Efficiency.
Modified Stirling Cycles	Generally Applicable	Low	Mechanically complex. High Efficiency.
"Displacement" Exapnsion methods	Generally Applicable	Low	Mechanically complex. High Efficiency.

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proposed by Taconis, which essentially embodies the general features of all these systems. Basically it has 3 spaces at different temperatures: (1) Hot, which for our discussion we shall suppose is at 700K; (2) Medium Temperature, which is the heat sink, and let us say that this is at room temperature (300K) and (3) Cold, which is the refrigerating space and let us say that this is at 100K. For our discussion therefore the three spaces are at temperatures in the ratios of 1 to 3 to 7. The basic concept is that one obtains refrigeration from the system by putting in heat, and not by putting in mechanical energy and by taking out heat at an intermediate temperature to the sink.

Fig. 2 shows a cylinder, diagramatically, with two pistons (P 1 and P 2) which are displacers capable of being moved up and down. The system is filled with a working gas for example, helium. The vertical lines in the centers of P 1 and P 2 in Fig. 2 represent tubes or similar passages which allow the gas to flow from one space to the other and at the same time act as regenerators.

The three diagrams of Fig. 3 represent three consecutive stages of the operation. The first stage (Fig. 3a) shows both pistons down as far as they can go with the top (Hot) space containing essentially all the working gas. Let us look at this on the PV diagram of Fig. 4a, which gives the pressure-volume relationship for the lower (Cold) space. The Cold space is at zero volume and its pressure, if there were to be any gas in it, (there always will be some in practice) will be the same as the pressure in the upper (Hot) space. Let us say that this pressure is seven atmos. This is the point a in Fig. 4a.

Now the next step is to go to the second configuration of Fig. 3b, where both pistons are pushed up to the top and all the gas from the upper (Hot) space goes down to the lower (cold) space. In the gas transference, if the regenerators are nearly perfect, the gas will emerge into the Cold space at the temperature 100K. This is illustrated on the indicator diagram of Fig. 4a by the path a to b. This expansion in the cold space creates refrigeration at the (constant) temperature of the cold space.

The next step is to let the lower displacer P 2 down, into the configuration shown in Fig. 3c. In this step the gas goes from the cold space to the Medium Temperature space, where it is compressed and the heat of compression is released into the sink. This is shown on the indicator diagram of Fig. 4a by the path b to c. The net re-

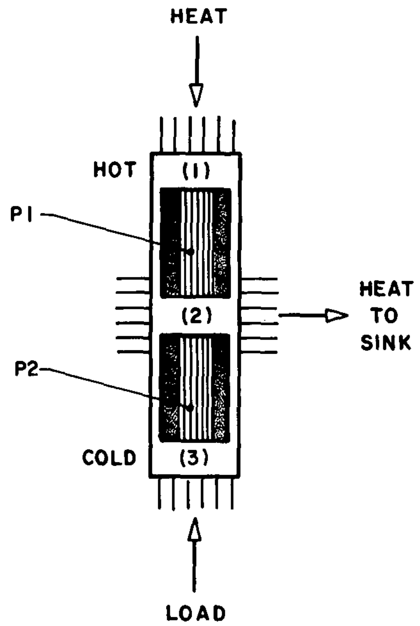


Fig. 2 Diagram of a Refrigerator proposed by Taconis, using heat rather than mechanical energy to drive it.

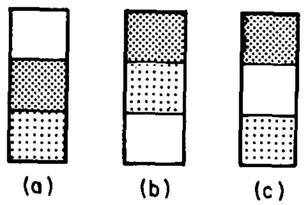


Fig. 3 Diagrams of the three main steps in the operation of the Taconis Refrigerator.

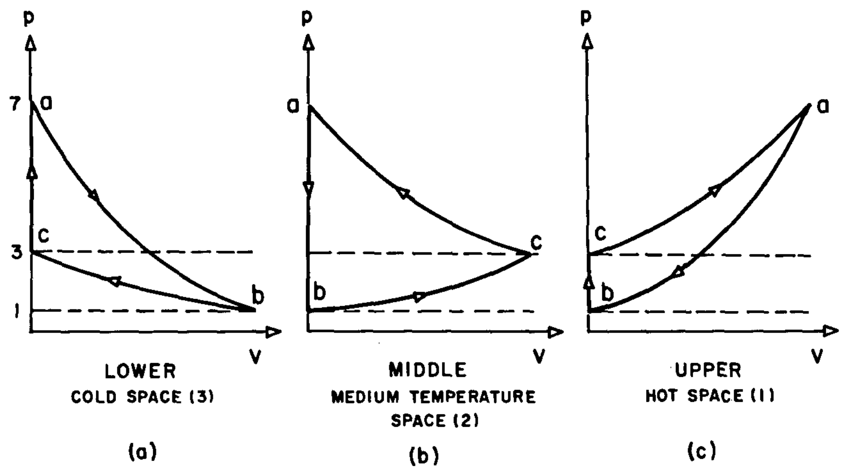


Fig. 4 PV diagrams for the working gas in the three spaces in the Taconis Refrigerator.

refrigeration is the difference between the areas under path a to b and b to c in Fig. 4a.

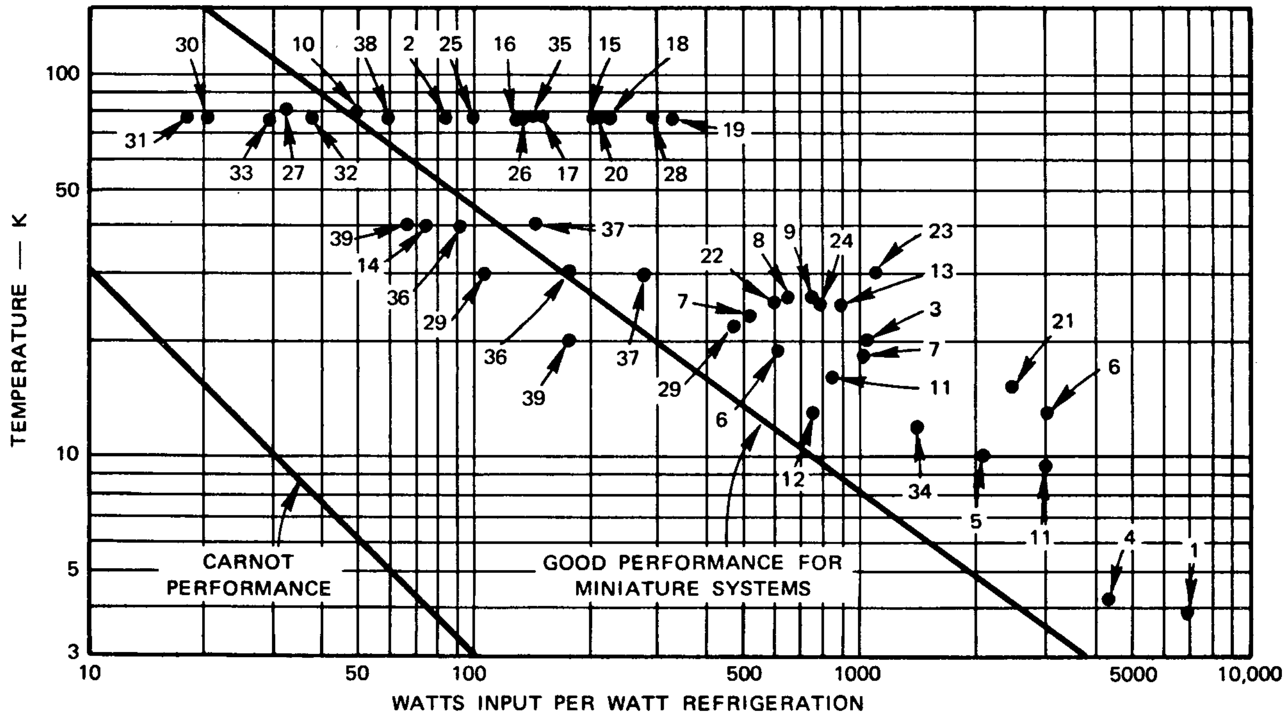
The final step is to go back from the configuration of Fig. 3c to the configuration of Fig. 3a. This step on the indicator diagram (Fig. 4a) is from c to a, so completing the cycle. The amount of refrigeration one gets therefore is given by the area inside that loop in Fig. 4a.

In the actual system that I have described here, it has been assumed that the regenerators are perfect. This would lead to a Carnot efficiency. The differences in practice between actual efficiency and Carnot-cycle efficiency are due in part to inefficiencies in the regenerators.

These Vuilleumier systems can be cascaded to go to still lower temperatures, just in the same way as the Gifford-McMahon or Stirling Systems can be cascaded. I foresee that they can be developed to provide temperatures in our range of interest; namely, below 20K. It is of interest furthermore to speculate on their possible use for automobile air conditioning, where one may employ the wasted exhaust heat to run the refrigerator, rather than mechanical energy.

Now we may discuss the efficiencies of various small scale and medium scale systems as functions of temperature. Fig. 5 shows some actually observed data on the efficiencies of a great number of different miniature refrigerators. This Fig. 5 is taken from an ONR Technical Report on "Miniature Cryogenic Refrigerators" by Dr. W. S. Goree and myself.[1] It shows the ratio of the input watts per watt of net refrigeration as a function of the refrigeration temperature. This ratio is the reciprocal of the coefficient of performance, (1/C.P.). Each point in Fig. 5 represents the performance of a real machine which exists or did exist and they are listed in Table IV. The curves shown in Fig. 5 represent the ideal Carnot performance and a estimated curve for good performance of miniature systems which was published previously.[2]

It will be seen that at the lower temperatures the performance of existing cryogenic refrigerators fall short of the estimates, whereas at the higher temperatures the performances are in many cases better than the estimates. It is of value to note, for example, that at about 4K, the data show that about 2000 watts input are required per



(Fig. 5)

INPUT POWER PER WATT OF NET REFRIGERATION AS A FUNCTION OF REFRIGERATION TEMPERATURE

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Table IV
Listing of the Cryogenic Refrigerators, the properties of which are shown in Figures 5, 6 and 7.

Manufacturer	Refrigerator	Temperature	Identification Numbers For Figs. 5, 6 and 7
Air Products	E-311	3.3K	1
	I-1	30K	2
British Oxygen	IR16-MK11	12K	3
Cryogenic Technology	400	3.8K	4
	0110	6.5K	5
	1020	12K	6
	350	15K	7
	120/RC-30	19K	8
	0125	19K	9
	C77	25K	10
Cryomech Inc.	GB02	7.5K	11
	GB12	9K	12
	AL01	23K	13
	AL02	23K	14
Garrett Airesearch	133386	77K	15
	133488	77K	16
	144406	77K	17
	800334	77K	18
	800398	77K	19
	800656	77K	20
Hughes Aircraft	Vuilleumier	15K	21
	Vuilleumier	25K	22
	Vuilleumier	30K	23
	Stirling	25K	24
	Vuilleumier	77K	25
	Vuilleumier	77K	26
	Stirling	80K	27
	Stirling	80K	28
Malaker Corporation	VII-C	17.5K	29
	VII-R	40K	30
	XX	40K	31
	XIV-A	45K	32
	XV	54K	33
North American Philips Corporation Philips Laboratories	Stirling	9K	34
	Vuilleumier	77K	35
U.S. Philips Corporation Norelco Cryogenics Div.	42100	20K	36
	42151	20K	37
	Microcryogem	40K	38
Philips, Eindhoven	X-20	12K	39

watt of refrigeration for miniature systems. Fig. 5 shows, that as one goes down in temperature the coefficient of performance decreases rapidly. For example at 10K one has $(1/C.P.) \approx 700$, which is to be compared with the value of about 2000 at 4K. In thinking therefore of systems to work with superconducting devices or other superconducting systems, one has to bear this strong variation of C.P. with T in mind in projecting the overall design. One has also to consider the volume and weight.

Fig. 6 shows for the same set of miniature refrigerators what the weight of the refrigerators is per watt of refrigeration as a function of temperature. Again, it is clear that in going to the lower temperatures the refrigerator weights per watt of refrigeration increase markedly. For example, at 4K the weight is about 400 pounds per watt. Of course these systems are not necessarily optimized but I think these data give a fair guide as to what one may expect in the current state-of-the-art. Fig. 7 shows the volumes of the systems, as a function of temperature where the volumes are expressed in cubic feet per watt of refrigeration. Again one notes the same general tendency.

Figs. 5, 6 and 7 show that, at least for miniature cryogenic refrigerators, the higher temperature range, about 60K to 80K, includes machines with more favorable relative performance and characteristics than the low temperature range. I think this is only to be expected, because this higher temperature range has received a great deal of research and development effort over the past ten years whereas relatively little attention has been paid to the low temperature range. I believe that in a few years one will see the performances of the lower temperature machines getting relatively much more favorable.

Now I shall make some comments on the lowest temperature range, which is of particular interest to the superconductivity field. Table V shows some information for 4.2K refrigerators of various sizes, giving the efficiency (in percentage of Carnot efficiency), weight and volume. The data are taken from smoothed curves drawn through data for the performances of twenty six refrigerators which have been previously presented by Strobridge.[3] Note that the figures for 1 watt refrigerative power are essentially the same as those quoted previously for miniature cryogenic refrigerators by Goree and myself.[2]

Fig. 8, taken from Strobridge's paper, shows graphically the relative efficiencies (in percentage of Carnot efficiency) of 3.5K to

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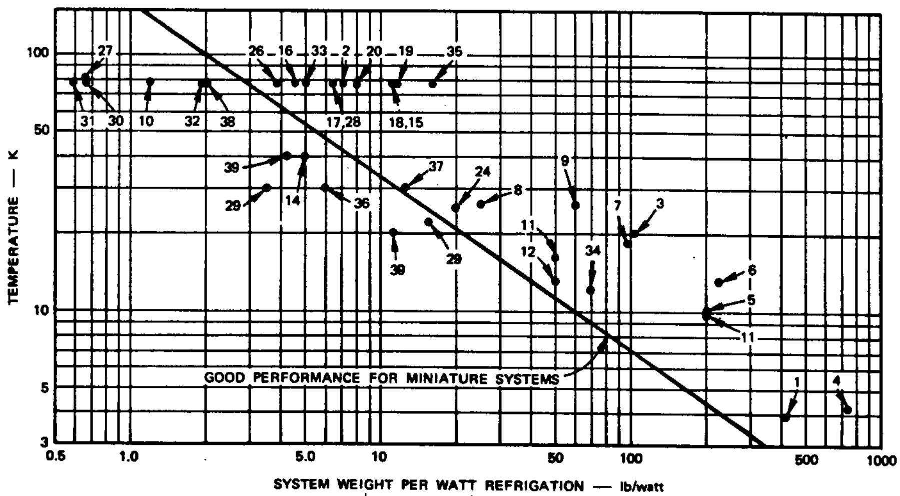

Fig. 6 System weight per watt of net refrigeration for miniature systems as a function of refrigeration temperature (See Ref. 1).

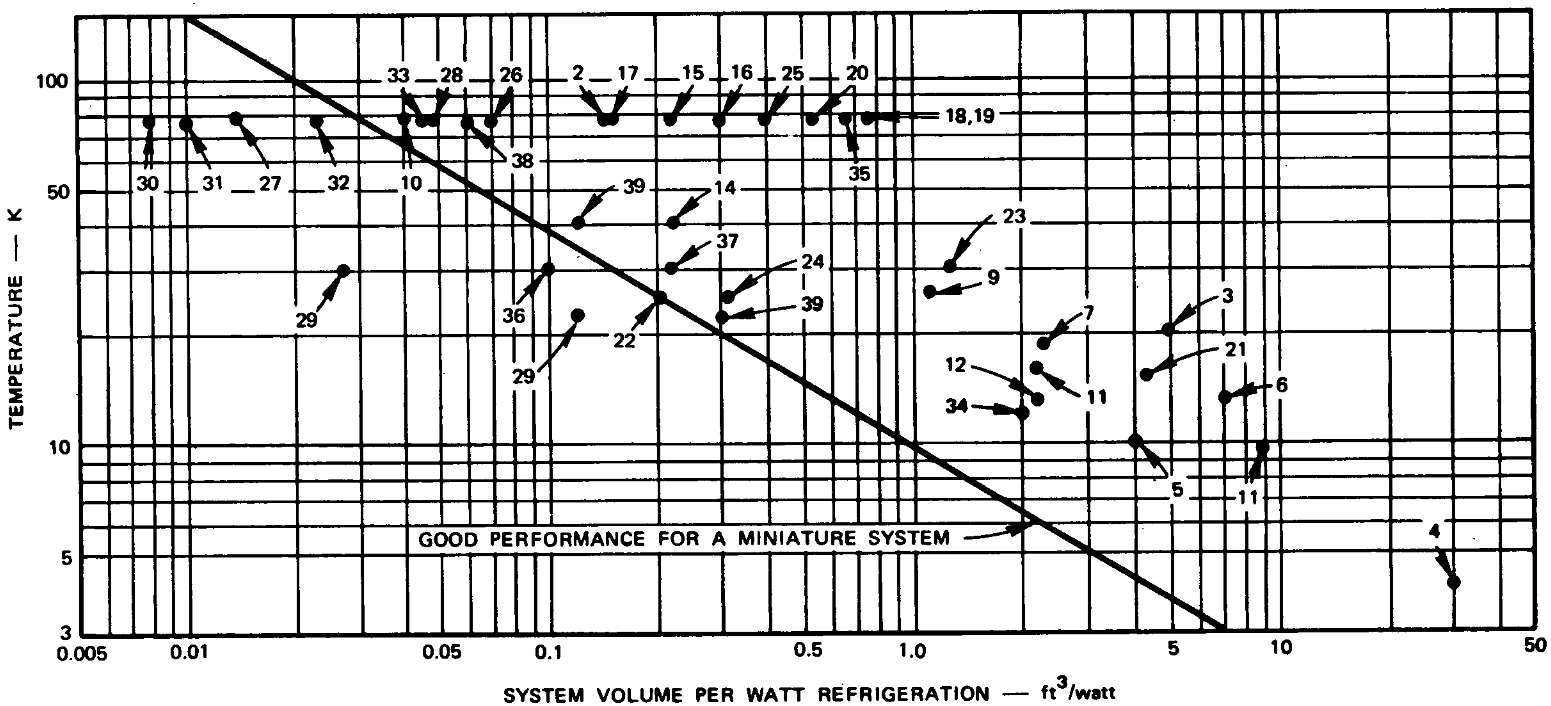

Fig. 7 System volume per watt of net refrigeration for miniature systems as a function of refrigeration temperature (See Ref. 1).

Table V
Data on 4.2K Refrigerators from Strobridge

Size (Refrigerative Power, Watts)	Relative Efficiency (% of Carnot) (Approx.)	Total Weight		Total Volume	
		kg	lbs.	m^3	ft^3
1	2	300	650	0.4	13
10	7	1,500	3,300	3	90
100	10	7,500	16,500	20	650
1000	15	40,000	90,000	150	5000

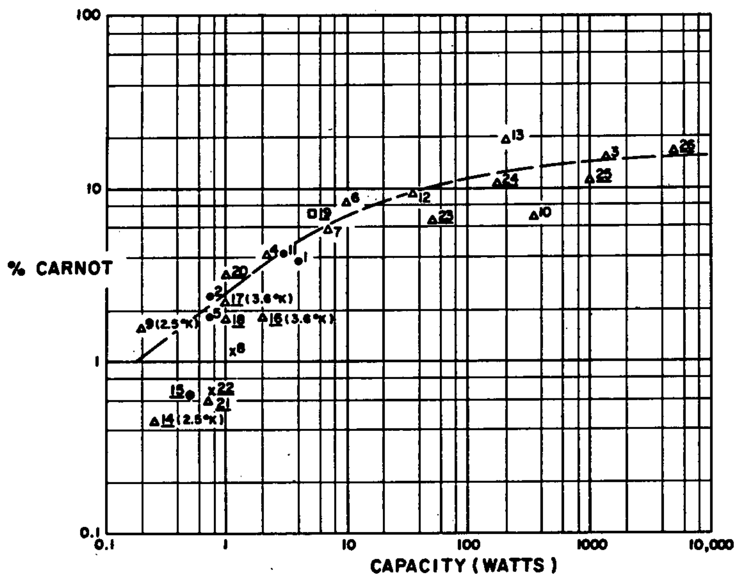

Fig. 8 Relative Efficiency in percentage of Carnot Efficiency of liquid helium temperature refrigerators as a function of refrigerator capacity (See Ref. 3).

4.2K refrigerators as a function of their refrigeration capacity in watts. Thirteen of the twenty six refrigerators of this figure were built and the data given is the observed data for them. A list of the actual refrigerative capacities, cycles of operation and liquid N_2 consumption for these thirteen machines is given in Table VI. Many of the points in Fig. 8 I regret to say do not represent real machines. Half of them represent real machines; the other half were under development or proposed at the time of Strobridge's paper[3] (Oct. 1968). Notice that at capacities of 100 to 200 watts, the relative efficiencies are about 8 to 10 percent.

Figs. 9 and 10 give the total weights and the total volumes for 3.5K to 4.2K refrigerators as a function of refrigerative capacity, taken from Strobridge's paper[3]. These figures, together with Fig. 8 enable one to make projections for cryogenic systems operating in the liquid helium region.

It is of interest finally to review briefly the 1.8K refrigerator which was developed by Cryogenics Technology Inc. initially for the superconducting linear accellerator at Stanford University and which has been installed elsewhere also. It is of particular interest because 1.8K is the refrigeration temperature, which results in production of superfluid helium. This is a fascinating feature, because superfluid helium at this temperature has an effective thermal conductivity of thousands of times that of copper and because it enables one to transmit cold over very large distances. In the Stanford accelerator the distance is about 500 feet. One can imagine a number of valuable reasons for piping cold over very long distances, for example for cooling down a number of different systems at the same time.

Some data on the 1.8K refrigerators are given in Table VII. (Courtesy of Mr. Milton Streeter of Cryogenic Technology, Inc.). The 15 watt machine, which is basically a Claude cycle, has relative efficiency of 3.8 percent that of the Carnot cycle and the 300 watt machine, which is the size installed at Stanford University, has relative efficiency of 7.2 percent that of the Carnot cycle. This latter figure is very close to the 8 to 10 percent previously quoted for a 4.2K refrigerator of similar size. They have made a very significant technical achievement in getting to this lower temperatore with efficiencies comparable to those of machines operating at higher temperatures.

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Table VI

Data on 3.5K to 4.2K Refrigerators included in Figures 8, 9 and 10. The Nos. in the left hand column refer to the numbered points in the figures. Data given by Strobridge.

No.	Capacity	Cycle	Liq. N_2 (1/hr.)
1	4	G-M	—
2	0.75	G-M	—
3	1400	Claude	130
4	2	Claude	—
5	0.75	G-M	—
6	10	Claude	1.0
7	7	Claude	—
8	1.25	Cascade JT	—
9	0.2	Claude	—
10	350	Claude	—
11	3	G-M	3.5
12	35	Claude	10
13	200	Claude	25

Points Nos. 14-26 in Figures 8, 9 and 10, were for refrigerators "under development or proposed" at the time of Strobridge's paper (Oct. 1968).

Table VII

Data on 1.8K Refrigerators (Courtesy of Mr. Milton Streeter, Cryogenic Technology, Inc.)

Refrigerature Power, Watts	Temperature	Cycle	Relative Efficiency (Percent of Carnot)	Liquid N_2 Consumption (1/hr.)
15	1.8	Claude	3.8	15
300	1.8	Claude	7.2	600

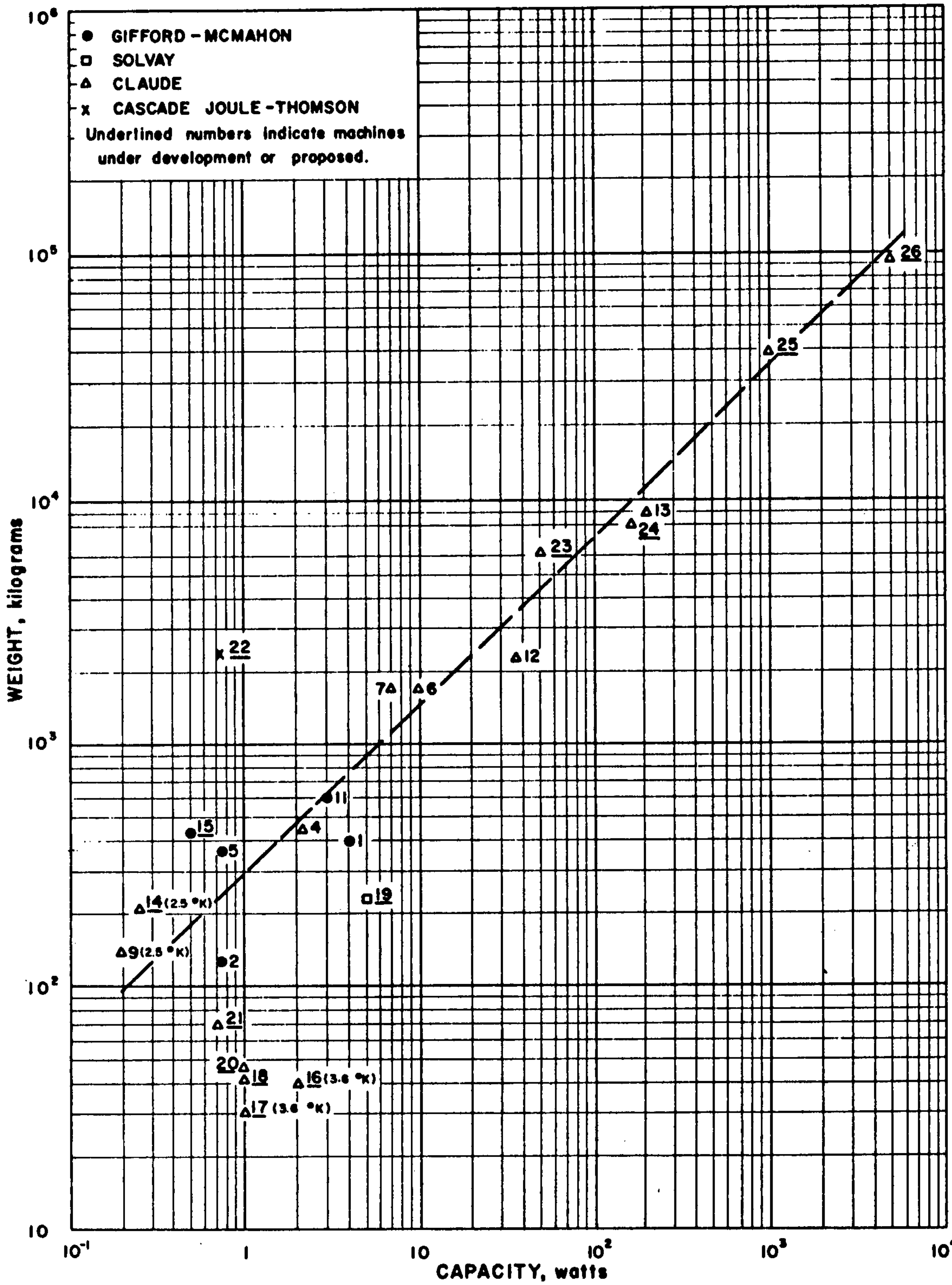

Fig. 9 Total weight of liquid helium temperature refrigerator systems as a function of refrigerator capacity (See Ref. 3).

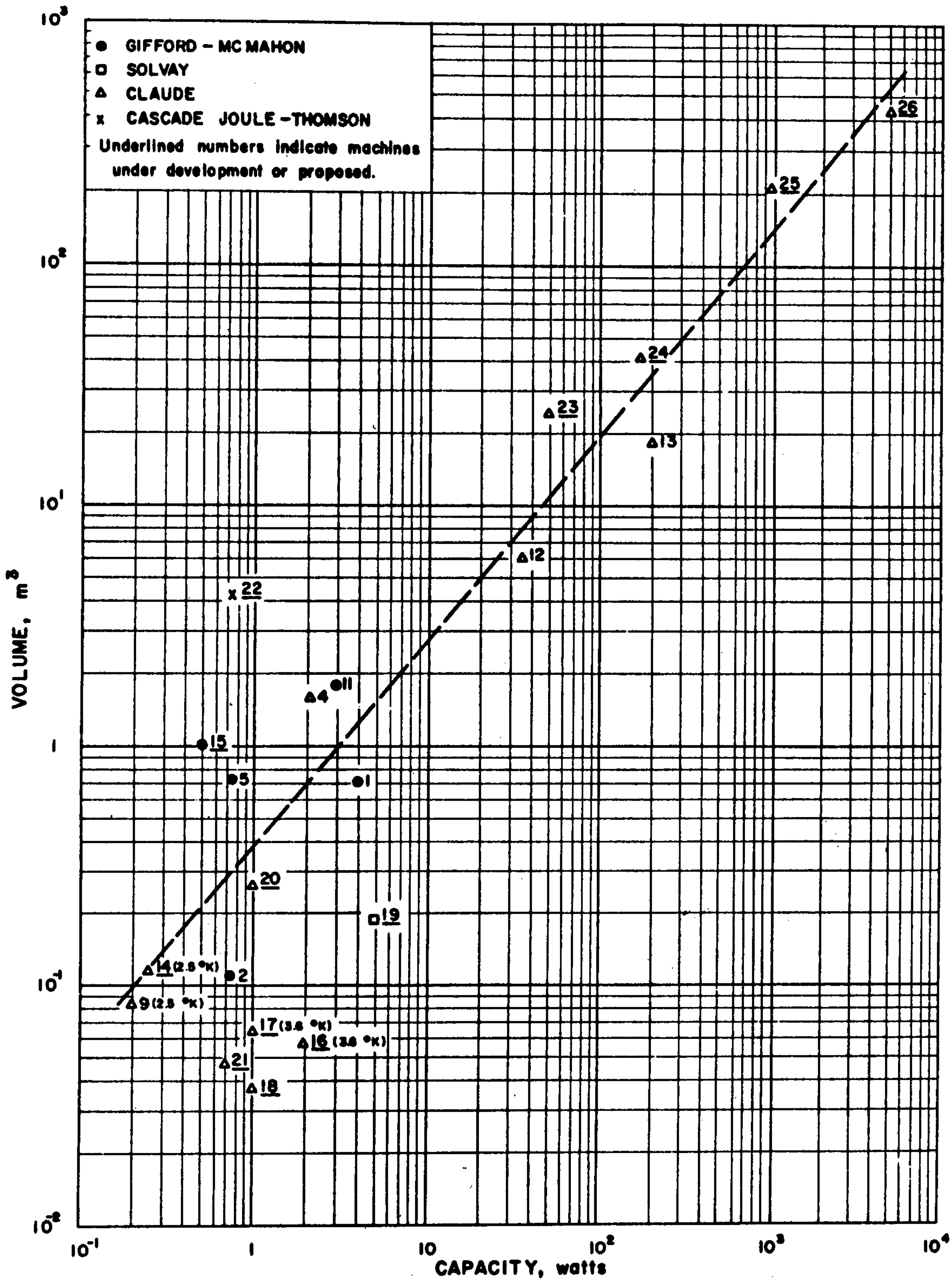

Fig. 10 Total Volume of liquid helium temperature refrigerator systems as a function of refrigerator capacity (See Ref. 3).

Finally I wish to make some speculations on what one may expect in the future.

An immediate problem, which I hope will be investigated in the immediate future, is the question of noise from the electric motors used in these refrigerators. This maybe a very serious problem for refrigerators used with small scale superconducting devices, such as Josephson magnetometers. It may entirely prohibit some current refrigerators from being used with such devices. This is a very important area for immediate investigation.

Another technological advance, which I see in future and which is actually being developed at the moment, is the development of expanders, both reciprocating and turbo, which allow liquefaction in the expander. This development will simplify systems operating at 4.2K and below, in that it will avoid the use of subsidiary Joule-Thompson circuits. I think this is a very important immediate development.

Another technological development, which I see in the future, is the successful development of cascaded Stirling cycles, Gifford-McMahon systems and possibly Solvay and Vuilleumier cycles to go directly down to 4K or thereabouts, without any hybrid additions such as Joule-Thompson circuits. This, I think, would be a very valuable future development and personally I think it quite possible.

Another development, which, I think, the future will see is the increased use of superfluid refrigeration, allowing temperatures below 2K to be transmitted over great distances from the refrigerating system.

Finally, I might say that I think in the future much more attention will be paid to the use of the rare isotope of helium, He^3, to go to temperatures below 4.2 degrees with various systems, even with simple systems like the Joule-Thompson system.

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References

1) "Miniature Cryogenic Refrigerators" J. G. Daunt and W. S. Goree, ONR Technical Report No. 1, Contract No. Nonr-263(73), Stevens Institute of Technology, Aug. 1969.

2) J. G. Daunt, R. A. Rossi, E. G. Jacobsen and S. F. Malaker, "Investigation of Gas Liquefiers for Space Operation," ASD-TDR-63-775, Malaker Laboratories, August 1963. See also reference 1 above.

3) T. R. Strobridge. "Technology of Liquid Helium". Editors: R. H. Kropschot, B. W. Birmingham and D. B. Mann, NBS Monograph 111, Oct. 1968, p. 55.

Discussion

Dr. Hein: I'm a little unsure of where you've left us at the moment. Are there in fact 4.2K refrigerators currently available?

Dr. Daunt: Yes. In Figs. 5, 6 and 7 and in Figs. 8, 9 and 10 I showed the efficiencies and other data of such systems. I recall that "500 Incorporated" (now known as Cryogenic Technology Inc.) made one set of the systems referred to in Figs. 5, 6 and 7 and Air Products and Chemicals another set. (See Table IV, items 1 and 4). These were, or are, hybrid systems; the first system used a Gifford-McMahon triply cascaded refrigerator followed by a Joule-Thompson circuit and the second system was basically a Claude system. They are, I believe, still available.

Dr. Hein: Do you have information on vibrational problems associated with cryogenic refrigerators?

Dr. Daunt: Data is available from some manufacturers. More attention to this problem however is warranted.

Dr. Hein: Is anybody now using these refrigerators in conjunction with superconducting or other devices?

Dr. Daunt: Oh yes, a great number are being used.

Dr. Hein: How many miniature refrigerators do you think have been marketed as of today? Do you have any idea? I mean in hundreds or so. I'm just curious.

Dr. Daunt: Well, I hesitate to make a guess. There are many people in the audience who could answer this better than I. However as far as I know, referring only to refrigerators which cool to 15K or below, my guess would be between 200 and 500. Enough of them have been made and sold to allow gathering of considerable operational data, particularly on the question of mean-time-between-failures. The results are quite satisfactory for some manufacturer's products and indicate that in many cases product reliability is meeting anticipated needs.

SESSION B

Wednesday Afternoon, 4 November 1970

Chairman: A. Chaikin
Naval Ship Systems Command

SUPERCONDUCTING ELECTRICAL MACHINERY

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1. INTRODUCTION

There has been considerable study and an appreciable amount of development work conducted in the United States, Europe and the USSR, on superconducting electrical machinery. The developments on AC machines have been heaviest in the USA and USSR, while the principal work on DC machines has been conducted in England and France.

The following remarks are intended to convey a basic understanding of superconducting electrical machines, to review the state of the art in general terms, and to identify the principal problem areas to be solved during future research and development.

2. DC MACHINES

Considerable attention has been applied to the development of superconducting homopolar dc machines. The largest efforts in this area have been conducted in the United Kingdom at IRDC, for the Royal Navy and NRDE.

The basic homopolar consists of a simple disc with brushes at the hub and periphery. Current is generated radially in the disc when it is rotated in a magnet field. Conversely, if current is applied to the disc in a magnetic field it will rotate and act as a motor. This concept is illustrated in Fig. 1. A basic drum type machine is illustrated in Fig. 2; the current is now generated axially in a radial field.

A large number of potential configurations for homopolar machines are present in Fig. 3. All those with brackets are presently being used or are planned for use. The homopolar machine is essentially a low voltage machine and several ways have been devised to raise the voltage and reduce the current. These include multiple discs, segmented discs and drums, and multilayer drums; the latter being essential for segmented rotors for use with liquid metal.

Current collection techniques fall into two separate groups, solid brushes and liquid metal brushes. The latter can be peripheral brushes with liquid metal maintained in the brush area, jet brushes with a continuous flow of liquid metal from the brush to the disc or drum, and the flooded rotor. The first two liquid metal concepts have been used extensively for conventional homopolar machines.

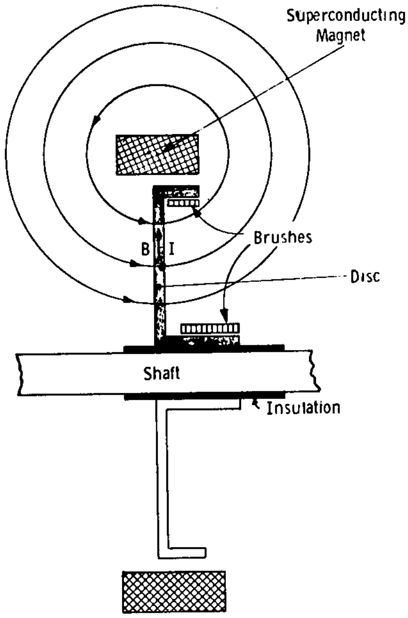


Fig. 1—Basic homopolar machine (disc type)

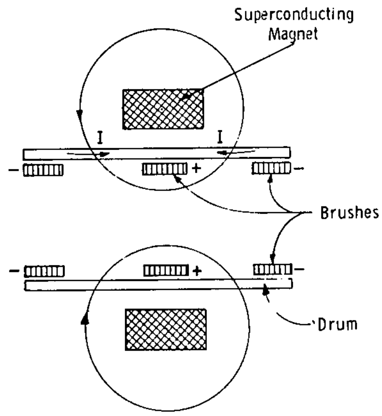


Fig. 2—Basic drum homopolar

FIG. 3 HOMOPOLAR TYPES

Disc		Magnet	
Single		(External)	Internal
Segmented		(External)	Internal
Multiple		(External)	Internal
Drum		**Magnet**	
Plain	(One)	(External)	(Internal)
Plain	(Two)	(External)	Internal
Circumferentially Segmented	(One)	(External)	Internal
Circumferentially Segmented	Two	External	Internal
Radially Segmented	(One)	(External)	(Internal)
Radially Segmented	(Two)	(External)	Internal

Conventional homopolar machines have been built using liquid metal sliprings over the past two decades, primarily for pulsing duty in nuclear and space applications. These machines have not been used extensively for normal commercial applications, presumably for economic reasons of one kind or another. No information has been obtained regarding the operating experiences with these machines. The power density in a homopolar machine is limited only by disc heating, losses, and provision for current collection. In order to utilize the flux developed by current state-of-the-art magnets, very high density current collection systems are required.

The development of superconducting magnets for homopolar machines is not considered to be a very difficult problem for stationary systems. However, the design of low heat leak systems for the high shock and vibration requirements on board naval ships will be a difficult problem.

The largest superconducting homopolar machine developed to date is the IRDC 3250 hp machine built for demonstration at Fawley Power station. The machine has a single superconducting annular magnet mounted outside a pair of segmented disc rotors. The rotors have 40 segments and alternate segments are connected in series electrically. The disc segment voltage is 27 volts, and with conventional solid brushes at the inside and outside periphery, the brush losses are quite significant. This machine is illustrated in Fig. 4.

The Fawley machine would be capable of about 8000 hp in rating if advanced superconductors and high current density brushes were used.

A development program being conducted by General Electric into the problems of current collection in homopolar machines has involved the construction of a small model homopolar.

The Laboratoire Central des Industries Electriques of Fontenay aux-Roses has been developing a 60 kW flooded rotor homopolar motor for the Ministry of Defense for the Army and Navy. The motor concept is a significant development in that all the space between the rotor and stator is filled with liquid metal and the sides of the rotating and stationary discs are insulated. The liquid metal in the connector (inner) side of the rotating disc will carry current parallel to the disc current and will, therefore, rotate with the disc. The liquid metal on the other side of the rotating disc will not carry current or rotate.

The viscous losses on the sides of discs and in the brush area are too high when the disc is rotated at high peripheral speed. The concept is, therefore, limited to low speed applications.

This unit has been operated at full current and torque on the stationary mode, but insulation separation problems on the rotor discs have prevented tests at speed. Discs with modified insulation coatings are now being installed in the machine and full performance

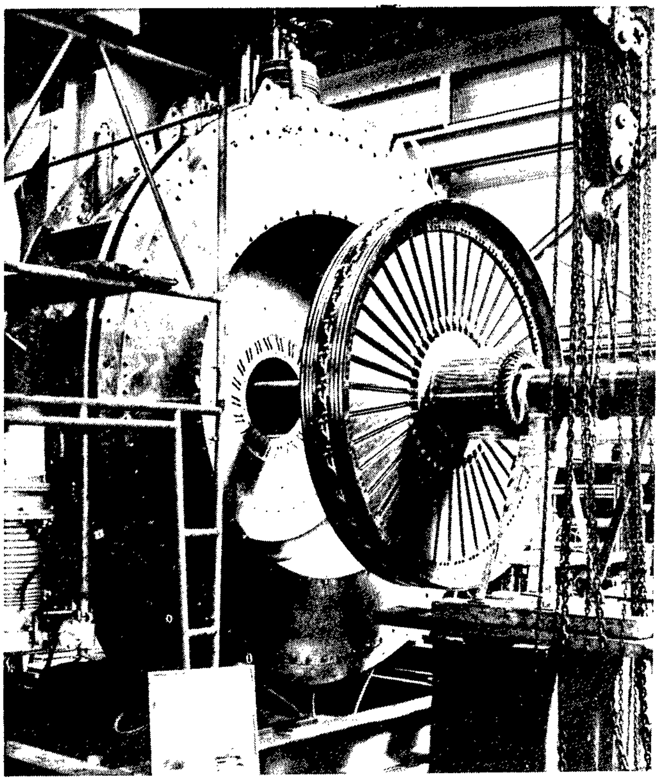


FIG. 4 MOTOR ASSEMBLY - INSERTION OF ROTOR

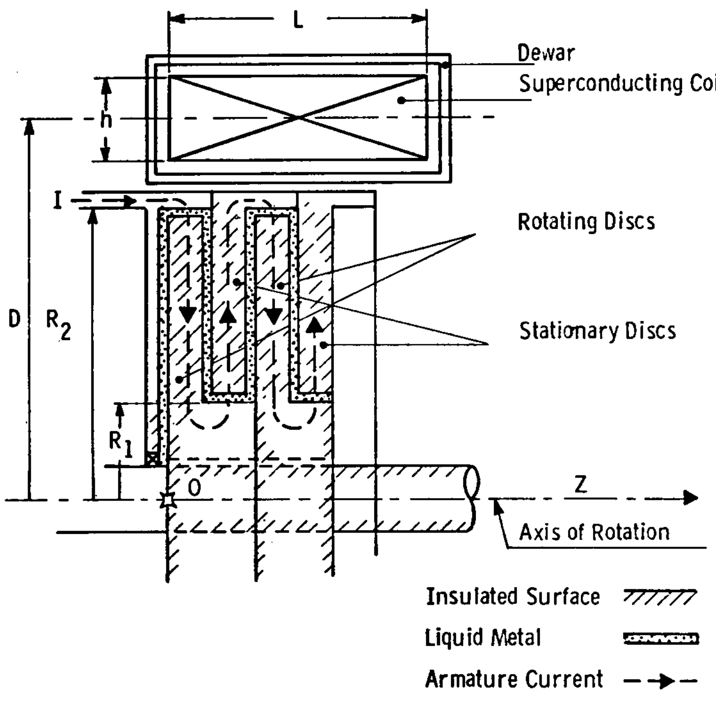


Fig. 5–Flooded rotor homopolar

tests will be conducted in the near future. A few other minor problems with seals have been encountered.

The general configuration of the flooded rotor design is illustrated in Fig. 5. The basic arrangement of the L.C.I.E. motor is presented in Fig. 6. Five rotor discs insulated from each other are mounted on the shaft. These are interleaved with stationary discs. All of the discs are set at angles such that the magnet flux will be perpendicular to each disc in the system.

The development of superconducting homopolar machines hinges entirely on the successful solution of all of the problems of current collection at high current densities.

NSRDL/Annapolis is developing a magnetically shielded acyclic machine in a configuration thought to be well adapted to shipboard applications. The magnetic circuit arrangement in the "shaped field" machine will permit liquid metal brush operation in very low magnetic field without sacrificing the high field capability of superconducting magnets, allowing high efficiency, low volume designs. The machine can be built in both disc and drum arrangements and easily configured for contrarotating propeller applications. A 10 disc laboratory unit of 1-1/2 foot diameter and 2-1/4 foot length is being designed to provide more than 1000 ft-lbs of torque. The disc arrangement is illustrated in Fig. 7.

3. ELECTRIC CONTACTS

The basic problem of evolving reliable and economic current collection systems for homopolar machines have been the object of large amounts of development work over the past 80 years or so. The prospects of solving these problems are improving steadily as new materials and technology is evolved.

Current collection in homopolars has been achieved using solid and liquid metal brush systems. These problems become more difficult in superconducting homopolar machines where much higher current densities are required in the current collection systems.

The use of solid brushes has involved the use of copper-graphite brushes in varying compositions. Some work has been conducted on silver based brushes, and brushes with special "fillings" have been developed for aviation use in rarified dry air where wear problems have been very severe.

In superconducting homopolar machines the high current density requirements virtually rule out the use of conventional solid brushes, However, a new composite solid brush is being developed in England by Morgan Crucible Co., Ltd., and IRDC. This brush will conduct 3-5 times the current density of conventional brushes at relatively low peripheral speeds. At high peripheral speeds the brush wear is severe.

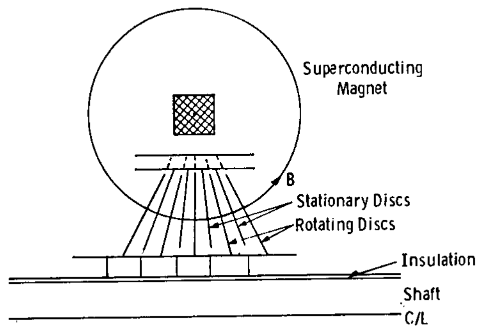
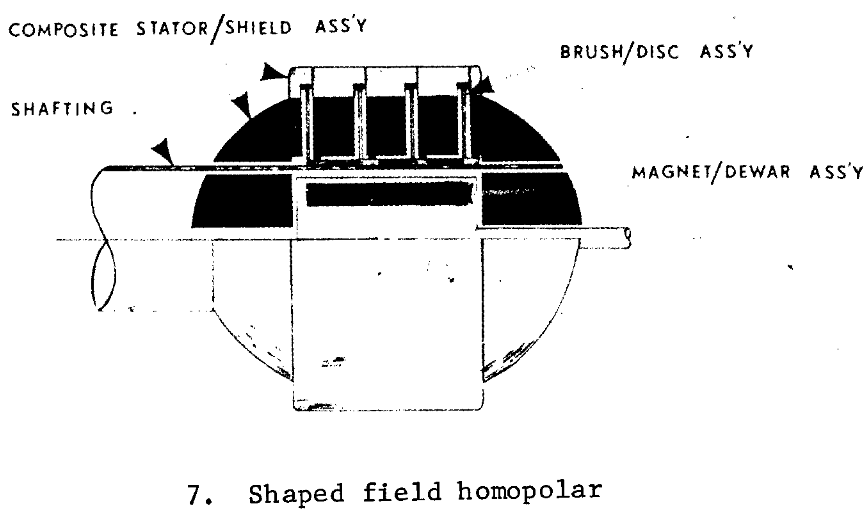


Fig. 6—L.C.I.E. machine basic arrangement

SHAPED FIELD DISC MACHINE



7. Shaped field homopolar

Homopolar machines with liquid metal contacts have been built for a number of years. These machines have utilized simple centrifugally fed collectors and jet collectors.

Most liquid metals are relatively hazardous in one way or another. The choices of liquid metals lie between sodium-potassium, indium-mercury, gallium-indium, and gallium-indium-tin. Sodium is highly reactive in the presence of moisture. Mercury is considered objectionable in many locations, gallium is slightly toxic and highly corrosive. Systems using these materials must be carefully designed to prevent risk of leakage, and to prevent oxygen from entering the system. The most commonly used liquid metal in homopolar machines is NaK. This metal is normally used with a nitrogen blanket.

Extensive studies have been conducted at Laboratoire Central des Industries Electriques to determine the most optimum liquid metal for use in superconducting homopolar machines. Under certain flow conditions, probably non-laminarly, these materials produce non-negligible quantities of scale or amorphous powder. This phenomenon is similar to the transformation of mercury, gallium, amalgums, and certain metal alloys with a low melting point, to a pulverulent matter. Transformation from liquid metal to powdered material is a change in state in which no chemical processes, especially oxidation, take place. It occurs in mercury, indium, gallium, lead, indium-gallium eutectic, sodium, potassium, and sodium-potassium eutectics.

These particles of powder are generally troublesome, since they take the place of a liquid alloy in systems whose operation is based on that alloy. The solution is to prevent the basic causes of the problem, namely, the presence of impurities and adsorbtion of gases. It is necessary to use very pure alloys or metals and prevent exposure to adsorbable gas atmospheres.

As a result of the extensive investigations at LCIE, mercury-indium was selected for use in the homopolar machine. Gallium-indium was rejected because black powder was generated in a closed system.

The tests to be conducted on the LCIE machine will be extremely valuable in terms of current collection problems.

A development program is being conducted at General Electric to develop current collection systems for superconducting homopolar machines. However, it is not possible to report on that work in this document.

A complete solution to the liquid metal current collection problem must, of necessity, include a complete understanding of the metallurgical, chemical, and safety problems involved in using liquid metals of the type suitable for this application. Substantial research and development is necessary to meet these goals.

4. AC SYNCHRONOUS MACHINES

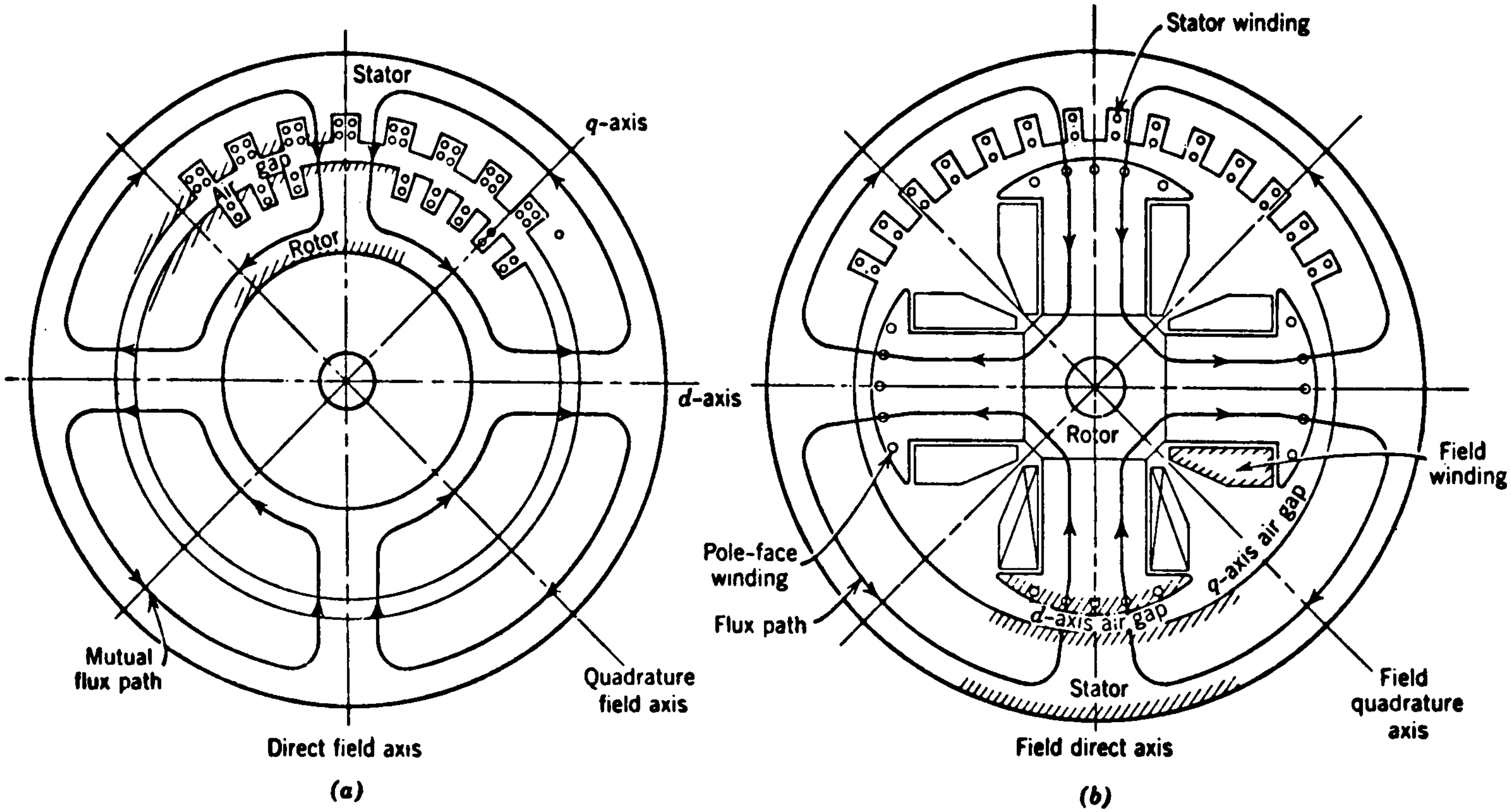
The conventional synchronous machine is utilized in two basic configurations, round rotor machines and salient pole machines. The former are used for high speed power generation applications. The salient pole machines are used for slower speed power generation, as synchronous motors and as synchronous condensers for power factor correction. These two types of machines are illustrated in Fig. 8.

When a synchronous generator supplies electrical power to a load, the armature current creates a component flux wave in the air gap which rotates at synchronous speed. This flux reacts with the flux generated by the field current, and electromagnetic torque results from the tendency of the two magnetic fields to align themselves. In a generator this torque opposes rotation, and mechanical torque must be applied from the prime mover in order to sustain rotation. The electromagnetic torque is the mechanism through which greater electrical power output calls for greater mechanical input.

During motor operation alternating current is applied to the armature winding, and DC excitation is applied to the field winding. The magnetic field of the armature currents rotates at synchronous speed. In order to produce a steady electromagnetic torque, the magnetic fields of stator and rotor must be constant in amplitude and stationary with respect to each other. The steady state speed is determined by the number of poles and frequency of the armature current. In a motor the electromagnetic torque is in the direction of rotation and balances the opposing torque required to drive the mechanical load. The damper windings mounted in the pole faces of the salient pole motors are used for starting the motors, in the same way squirrel cages are used in induction motors. When the motor is started there is relative movement between the field produced by the armature winding and the rotor. The damper winding will have a voltage induced and a current will flow round the winding. This will produce a torque in the same direction as the rotating field. The rotor will accelerate to a speed close to synchronous speed and then application of excitation to the field winding will cause the machine to synchronize.

The superconducting AC machine is illustrated in Fig. 9. The armature winding is wound to the same basic configuration as the conventional machine. However, no iron teeth are used. The stator may have an iron shield in place of the conventional stator which has slots for the armature windings. In large machines there may be some advantages from using an eddy current shield in place of the iron shield.

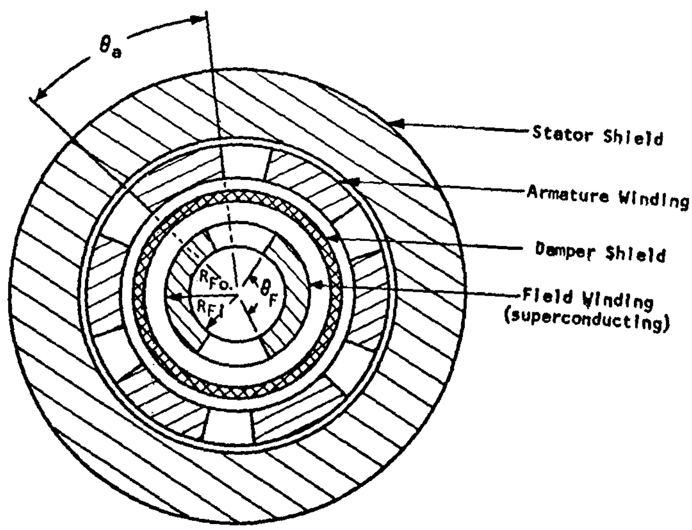
The field winding has the same basic configuration as those used in conventional machines, but is superconducting and must be maintained at close to 4.2°K. The damper shield between the field and armature windings may perform as a damping and starting winding and has the additional requirement of partially shielding the field winding from AC fields rotating in the air gap relative to the rotor.



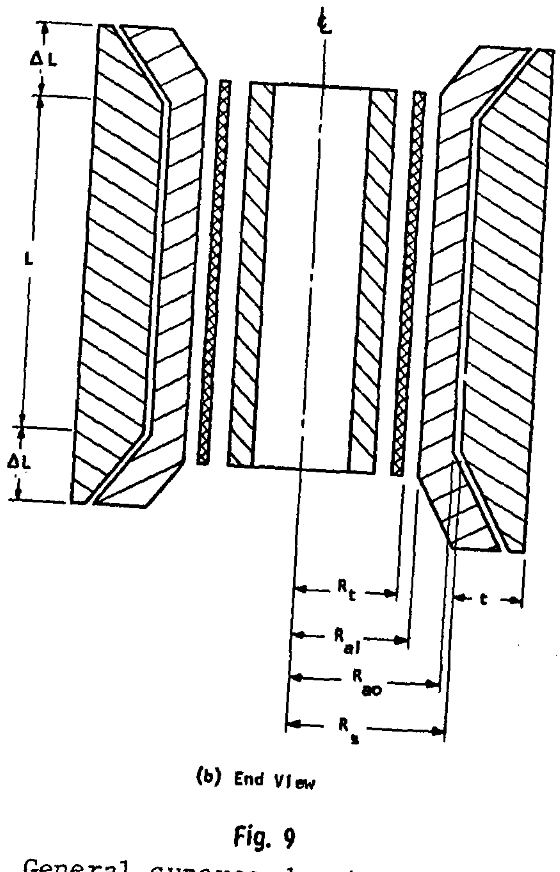
(a) Geometries for a uniform air gap, four-pole, synchronous machine. (b) Salient four-pole geometry.

Fig. 8

Conventional synchronous machines



(a) Cross-sectional view of superconducting machine



(b) End View

Fig. 9
General superconducting AC machine

The rotating dewar includes the field winding, its support structure, provision for cooling it with helium, means for transporting the helium into the rotor from the outside supply, special vapor cooled leads for excitation, radiation shields, damper shields, provision for a vacuum around the field winding and their cold parts. All of these components must be supported mechanically with a stable structure, unaffected adversely by the large contractions and expansions caused by cooling to 4.2°K and reheating. The helium transfer system for transferring helium to the rotating shaft is considered to be the most serious problem. Rotating transfer systems have been built for water and liquid nitrogen completely successfully. A helium transfer system has been built at MIT for use with the 80 kVA machine, and operated successfully.

The mounting and cooling of the field winding will be a very important design consideration. The field winding must be supported in such a way that no motion will take place due to the large electromagnetic forces and centrifugal loads, while adequate cooling surface area and helium ducting is provided for.

The damper shield provides the dual role of damping the rotor swings due to system disturbances and at the same time shielding the field winding from ac fields. AC fields in the field windings result in losses which may require excessive cooling or cause a quench. A damper shield can be designed to prevent most of the ac fields from penetrating the field, with the exception of very low frequency fields. The damper shield must be fabricated from a high conductivity material such as copper or aluminum, which must be supported mechanically. The attenuation characteristics of typical shields are illustrated in Fig. 10.

The most significant stator problems stem from placing the winding in the air gap. The winding is now exposed to the full field which is much higher than in conventional machines. The eddy current losses can be maintained at a low level by fine conductor stranding such as "Litz" wire. The stator winding is reduced to a generally weaker, more flexible structure which is no longer supported in slots. This winding must be attached to a structure which is tied solidly to the machine foundations and withstand forces due to transient torques. A number of sound solutions have been evolved for these problems.

A significant problem relates to the choice of stator shield required to prevent rotating fields inducing current and forces on adjacent objects, and reflections to the rotor causing dynamic instability. The choice lies between iron shields which carry the full flux and conducting shields which have high losses and tend to demagnetize the field. From an economic point of view the latter are very attractive. The iron shield tends to be very heavy.

Due to the lack of teeth the coil spacing makes the use of diamond end turns impractical. New end turn configurations must be selected.

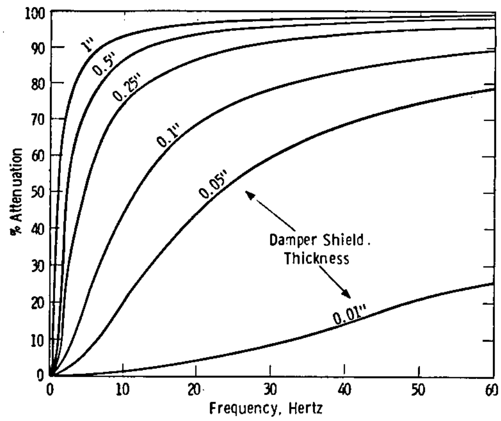


Fig. 10—Attenuation of AC fields due to a copper damper shield in a two pole machine (radius = 10")

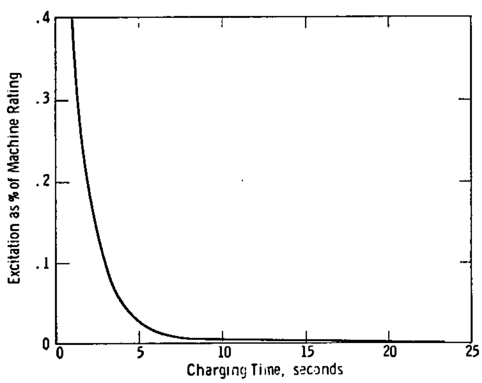


Fig. 11—Magnet excitation characteristics

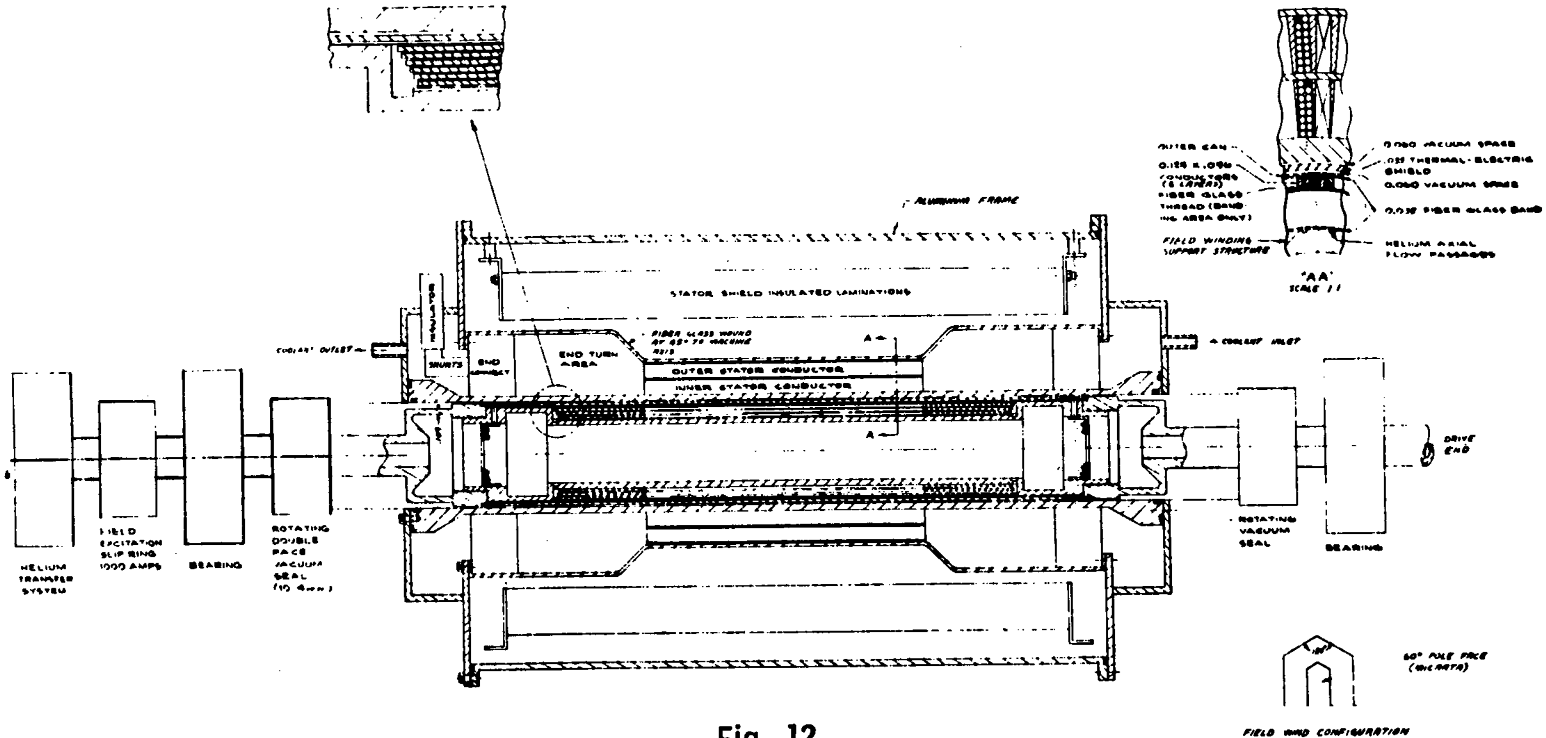


Fig. 12

MIT 2 MVA machine

The characteristics and performance of superconducting machines are very similar to conventional machines. The use of a high field tends to reduce the problems of obtaining desirable transient and synchronous reactances, and the design configurations may be maintained with a good deal of flexibility to obtain desirable reactances for a given application.

One important factor to be considered is the large stored energy in the field winding. This makes the changes in the field flux level a slow process if the field excitation systems are to be maintained at an economic level. In general the excitation power levels can be maintained at an economic level if field changing times are kept above 5-10 seconds for a complete change in field flux. This is illustrated in Fig. 11.

The MIT design for the 2 MVA machine is the most advanced design available today. This design is illustrated in Fig. 12.

The superconducting synchronous machine has potential for very large savings in weight and volume, which make it particularly attractive where those parameters are at a premium. The volume comparison between superconducting and conventional AC machines is illustrated in Fig. 13.

The weight of aircraft generators is of great importance. Very high speed machines have been used extensively in order to reduce the weight substantially. However, the use of large machines for aircraft use has been limited due to high stresses in rotor, which has led to lower speeds and higher weights. The specific weight of aircraft generators is related to machine rating in Fig. 14. A steep increase in specific weight is indicated at ratings in excess of 2 MVA. The superconducting machine alternative will have a much smaller rotor and may, therefore, be built in much larger ratings before the stresses get severe. The weight advantages are self evident.

The actual size of a 5 MVA generator is illustrated in Fig. 15.

5. SUPERCONDUCTING MATERIALS SURVEY

Superconducting materials capable of carrying current densities up to 10^5 amperes/cm^2 in applied fields of 50 kilogauss have been known since the early sixties, but only in the past few years have they appeared in a form where their use in rotating machinery under realistic conditions is feasible. Recognition of the basic need for a reduction in the size of the individual current carrying superconductors to achieve more stable characteristics by reducing the hysteresis and eddy current losses which occur under ac field conditions led to the recent development of multifilament conductors. These conductors have improved properties which make their use in superconducting field windings in motors and generators appear extremely attractive. At present, conductors of this type are only available made from the ductile alloy niobium-titanium, due to the

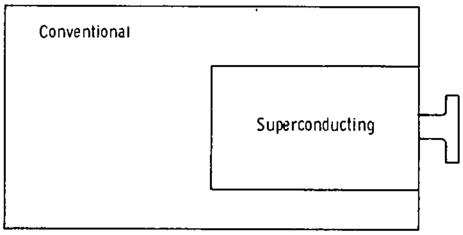


Fig. 13—Comparison of volume for conventional and superconducting AC generators at 25 MVA, 3600 RPM

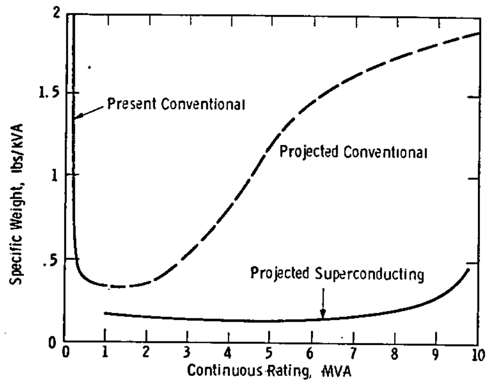


Fig. 14—High speed airborne generators, specific weight projections

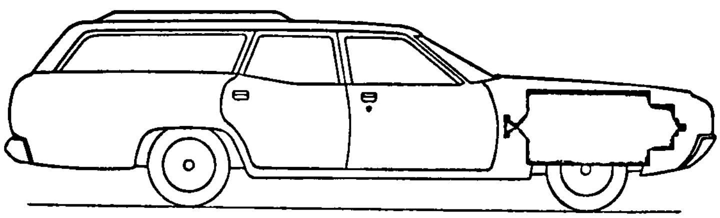


Fig. 15

5 MVA size illustration

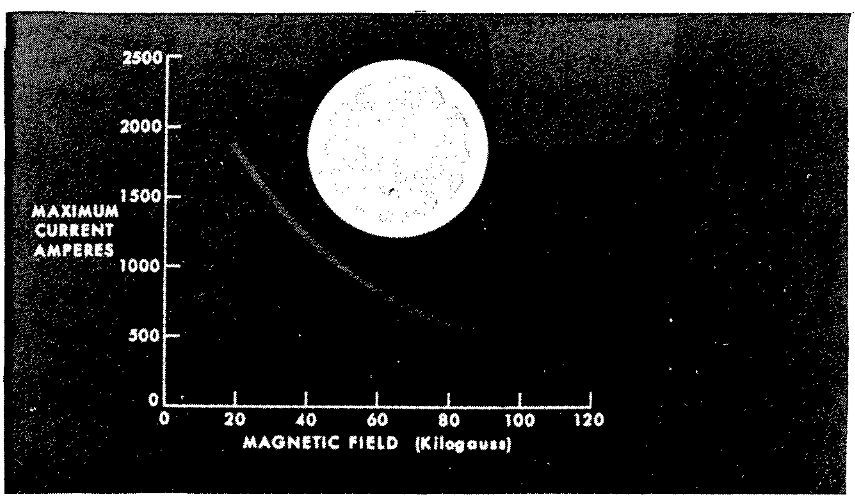


Fig. 16

Microsections of typical multifilament conductors with a copper matrix nigh degree of cold work required in their fabrication using current metallurgical techniques. This material has a critical temperature near 10°K so that operation at or below the normal boiling point of liquid helium, 4.2°K, is mandatory if a significant improvement over conventional winding current densities is to be achieved at a reasonable value of magnetic field, say 50 kilogauss. A state of the art multifilament conductor illustrated in Fig. 16 has the following characteristics. A niobium-titanium alloy, with a composition near 50-50 atomic percent, is incorporated in the form of 5000 fine filaments with a diameter of .0006 inches, in a copper matrix .080 inches in diameter. The filaments are twisted inside the matrix to improve stability. A critical current of about 70 amperes in a steady field of 50 kilogauss is usual for the above type of wire. The electrical losses are near 10 mW/cm^3 for a field sweep rate of 50-100 kilogauss/second with a normal metal to superconductor ratio of between 1.5 and 2.0. Higher current capacity conductors are made by cabling techniques from wires of this type, transposition usually being employed during the process, with often some subsequent further compaction to improve the packing factor. Cabled conductors can readily be produced with current carrying capacities in excess of 1000 amperes. An alternative approach to the manufacture of high current conductors has also been followed in some cases, whereby a multifilament conductor of the requisite size is formed directly with a solid matrix.

6. SHIP PROPULSION

There are many alternative electric propulsion systems available for use with gas turbines, steam turbines and diesel engines. The alternative systems are illustrated in Fig. 17, in terms of constant and varying speed prime movers. The systems involve a choice of all DC homopolar machines, all AC machines, or a hybrid system using an AC generator and DC motor.

A frequency conversion system suitable for use with a constant speed prime mover is the cycloconverter. The cycloconverter is a frequency changer consisting of an array of solid state power switches in a cyclic sequence, as illustrated in Fig. 18. These switches apply proper segments of the ac supply voltage to the load so as to synthesize an output voltage of desired frequency and amplitude. For instance, when the switches encircled with dashed lines are closed, the output voltage of E_{x-y} is provided by a segment of the A-B line voltage. Applying this variable frequency ac power to an ac motor (synchronous or asynchronous), a high efficiency, variable speed, commutatorless ac drive is obtained which matches in every respect the performance of high quality dc drives. Operating from a source or generator of frequency F_s, a continuously variable output frequency F_o ranging from 0 to about 2/3 F_s can be obtained. Within this frequency range, only negligible additional losses are generated in the ac machine by the "ripple". Cycloconverter ac drives can be built to any desired rating. The largest such drive built to date has been installed at Le Havre, France, and is rated at 9000 HP.

FIG. 17 ELECTRIC PROPULSION SYSTEMS

Prime Movers	Gas or Steam Turbines, Diesels

Constant Speed Prime Movers

DC Homopolar Motor and Generator
  Field Excitation Control

AC Synchronous
  Cyclo Converter Frequency Control

Hybrid Synchronous Generator and Homopolar Motor
  Silicon Controlled Rectifier Controller

Variable Speed Prime Movers

DC Homopolar Motor and Generator
  No Electrical Control (except reversing)

AC Synchronous
  No Electrical Control (except reversing)
  (no zero speed locking)

AC Synchronous
  Partial Speed Variation Plus Low Power
  Cyclo Converter

AC Synchronous - Synchronous Induction
  Partial Speed Variation + Reversing Switches

Hybrid Synchronous Generator and Homopolar Motor
  Silicon Controlled Rectifier Controller

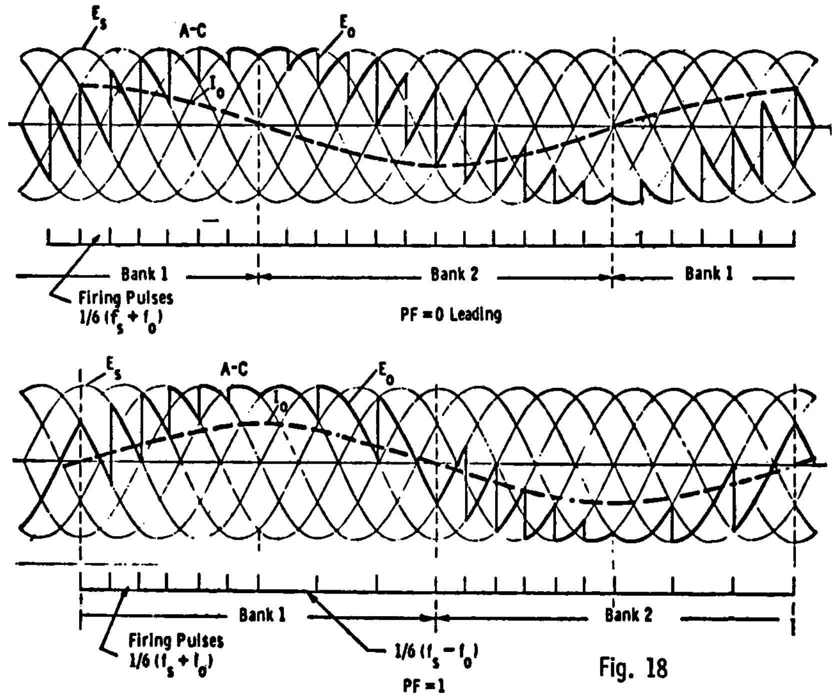


Fig. 18

Cyclo converter

FIG. 19 UNITED STATES ACTIVITY IN SUPERCONDUCTING MACHINES

Organization	Homopolar		AC Synchronous	
	Studies	Development	Studies	Development
MIT	X		X	X
AVCO	X		X	X
MCA	X		X	
Westinghouse	X		X	X
G.E.	X	X	X	
Lear Siegler			X	
General Motors	X			
NASA - Lewis	X		X	
USAF - WPAFB			X	
US Army - MERDC			X	X
US Army - Fort Eustus			X	X
US Navy - NSRDL	X	X	X	X
Dynatech			X	X

7. GENERAL STATE OF THE ART

Much of the prior discussion relates to the State of the Art of superconducting electrical machines. Superconducting machines have been developed in the two major areas of alternating current synchronous and direct current homopolar machines. The development of AC machines has been heavy in the United States and the U.S.S.R., while the principal homopolar efforts have been conducted in England and France. The activities in the United States are presented in Fig. 19. The activities in foreign countries are illustrated in Fig. 20.

The particular machine developments completed or currently in execution are tabulated below:

7.1 D.C. Homopolar Machines

Organization	Machine	Status
G.E.	Small model	Current development
IRDC	50 HP motor	Completed
IRDC	3250 HP motor	Completed--undergoing tests
IRDC	1200 HP motor	Current development
IRDC	1000 KW generator	Current development
LCIE	60 KW motor	Current development
ORSAY	$2x10^6$ amp pulsing generator	Current development
TOSHIBA	Model machine	Current development
MITSUBISHI	Model machine	Current development
HITACHI	Model machine	Current development

7.2 D.C. Heteropolar Machines

LPI-USSR	Motor	Completed

7.3 A.C. Synchronous Machines

MIT	80 KVA generator	Completed
MIT	2000 KVA generator	Current development
AVCO	8 KW generator	Completed
NSRDL	8 KW generator	Completed
LPI-USSR	100 KW generator	Completed
LPI-USSR	1000 KVA generator	Current development

The survey yielded a broad comprehensive picture of the superconducting electrical machine field of activities. The activity in the field is growing quite rapidly especially in the areas of dc homopolar machines for ship propulsion and ac machines for power generation.

The superconducting homopolar will be a very valuable machine for a variety of "high" power ratings when the current collection problem is solved completely, technically and economically. The activities being conducted have substantial promise of solving these problems, but a large scale effort may be necessary to achieve a complete solution.

FIG. 20 FOREIGN ACTIVITY IN SUPERCONDUCTING MACHINES

Country Organization	Homopolar		AC Synchronous	
	Studies	Development	Studies	Development
Great Britain				
IRD	X	X	X	
CERL	X		X	
C of AERO	X		X	X
EEC/AEI	X	X	X	X
Parsons	X		X	
Imp. Coll	X		X	
Navy	X	X		
France				
CGE/Althsholm	X		X	
EDF			X	
LCIE	X	X	X	X
CFTH			X	
ORSAY	X	X		
W. Germany				
Siemens	X		X	
AEG			X	
Sweden				
ASEA			X	X
Japan				
Tokyo Toshiba	X	X	X	
Mitsubishi	X	X		
Hitachi	X	X		
Switzerland				
Brown Boveri			X	
USSR*	X		X	X

* A superconducting heteropolar generator was developed

The consistently optimistic projections by generally conservative heavy electrical machine engineers, regarding the successful development of superconducting ac machines, was very encouraging. None of these engineers felt that the problems were severe enough to question the feasibility of the application to power generation. The sound work being conducted at MIT tends to support this optimism.

8. BASIC PROBLEMS OF SUPERCONDUCTING MACHINES

The basic problems of superconducting electrical machines consist of problems common to all types of machines and those peculiar to either DC homopolar or AC synchronous machines. The general problems for all machines are:

- Voltage control. The large inductance of the superconducting field winding prevents rapid changes of flux at reasonable excitation power levels.
- Low temperature materials. There is limited information on structural and insulating materials suitable for use at cryogenic temperatures.
- Refrigeration systems. Systems have not yet been developed for suitable use on vehicles such as ships, and for high shock and vibration.

The specific problems related to DC homopolar machines are:

- Current collection. The dense packing required in superconducting homopolar machines results in very high current densities at the current collection zones. This high current density prevents the use of conventional solid brushes at the normal ambient conditions. The choice of current collection system lies between new composite solid brush systems and liquid metal systems using sodium-potassium or gallium-indium alloys. The current collection problem is aggravated by the reversing requirements for ship propulsion which require a stationary machine supplying torque. The flooded motor design may solve this problem.
- Liquid metal. The selection of a liquid metal is governed by many factors including losses, corrosion, safety and cost. Both of the potential liquid metal selections have problems in most of these areas.
- Dewar structure. The superconducting field winding must be supported within the dewar, withstand high shock and vibration and yet have a very small heat leakage from the ambient.
- Rotor insulation. The disc or drum windings of the homopolar machine must be insulated electrically from the shaft and each other. The insulation must carry the full transient torques of the machine. The insulation must be sealed from contact with the liquid metal to prevent short circuits. Insulation must be applied to the sides of the discs on the flooded machine and not wear rapidly.
- Magnetic shielding. Shielding of the DC field will require heavy iron magnetic structures or sophisticated magnet systems.

The problems related to the AC synchronous machines are presented below:

- Rotor dewar system. The rotating dewar includes the field winding, provision for cooling it, means for transporting helium into the rotor, reduction of heat leakage into the field, current carrying leads, provision for a vacuum. Particular attention must be applied to the helium transfer system, mounting and cooling of the field winding.
- AC in the rotor. The superconductor will absorb a small amount of AC losses due to AC fields from the stator. It is necessary, however, to minimize these AC losses by attenuating most of the field at the rotor, using a high conductivity damper shield. Complete understanding of this entire problem will require substantial development.
- Stator winding. The stator winding will, in most machines, be mounted in the air gap and be exposed to the full magnetic field. The correspondingly high eddy current losses will require the use of finely stranded conductors, and new conductor configurations must be evolved. This winding will require new end turn arrangements, since diamond shaped end connections will no longer be feasible. Sound methods of developing a very strong stator winding structure must be evolved.
- Magnetic shielding. The rotating field of the machine must be shielded to prevent strong fields from inducing currents and forces on adjacent objects, and reflections to the rotor causing dynamic instability. The choice lies between iron shields which carry the full flux, and conducting shields which have high losses and tend to demagnetize the field.
- Structure borne noise. The magnetic forces on the shield will tend to generate structure borne noise. This noise will be somewhat less than that experienced in conventional machines, but will require a careful study and development to reduce it to a very low level.

9. REFERENCES

All of the important references on the technology of superconducting electrical machines are contained in:

Survey of the State of the Art of Superconducting Electrical Machinery.

Report prepared by Westinghouse Electric Corporation for the U.S. Navy, Office of Naval Research, Code 421, Contract #N00014-70-C-0246. November 1970.

DISCUSSION - MR. MOLE

Dr. Langenberg, RAI: Does the weight calculation for the airborne machine include the refrigerator?

Mr. Mole. Yes. That is assuming that we are going to have refrigerators which weigh less than 200 lbs. and produce several watts of refrigeration.

Dr. Hein, NRL: Has anyone done any shock and vibration testing on the whole motor-dewar setup?

Mr. Mole. No. We are now conducting dynamic analysis for shock and vibration. The light, stiff rotor design has inherently good shock and vibration characteristics.

Dr. van Reuth, NSRDL, Annapolis: You showed that Westinghouse motor in a car that cranked out roughly 30 times as much power in the same weight and volume.

Mr. Mole. The intent of the illustration is to give some idea of the size of the generator. The machine weighs about 600 lbs.

Dr. van Reuth: One-tenth of a lb. per hp?

Mr. Mole. Yes. The machine is very high speed. If you compare it with your projections for low speed machines you will find it correlates very well.

Unknown Person. Does that include shielding?

Mr. Mole. Yes.

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A SURVEY OF SUPERCONDUCTING MAGNET TECHNOLOGY

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INTRODUCTION

This review will generally avoid in-depth discussion in order to present an overview of the technology with emphasis on the several physical parameters which most influence magnet design.

High field, high current superconductivity has just completed its first decade of development. J. E. Kunzler of Bell Telephone Laboratories began the period by announcing his breakthrough development of a new Nb_3Sn conductor.[1] The decade since Kunzler's announcement has been marked by almost frantic activity to understand and utilize this very promising new tool. The major obstacle to successful engineering design of superconducting magnet systems has been electrical instability; and in this area two additional breakthroughs have developed.

Conventional electromagnets have been described as the world's most inefficient devices, often consuming millions of watts of electricity only to overcome the ohmic resistance of the best conductors. By contrast the perfect conductivity at cryogenic temperatures discovered by Onnes in 1911[2] gave hope of very efficient high field magnets. This goal has proven to be an elusive one. Magnet performance was first limited by the effect of magnetic fields in restoring normal conductivity. Later electrical instabilities were the more frequent limit.

THE CRYOGENIC ENVIRONMENT

Some knowledge of the strange physical environment at cryogenic temperatures (e.g. 4.2 K at which temperature most superconducting magnets operate) is necessary to appreciate the problems of superconducting magnet engineering. Copper, normally a good electrical conductor, becomes a much better conductor with electrical conductivity generally 100 times better than at room temperature. The thermal conductivity of metals generally improves with decreasing temperature, then falls rapidly as conduction electron states condense below 20°K. The heat capacity of metals also approaches zero as the temperature falls. Structural materials become stronger but more brittle at cryogenic temperatures.

Various aspects of cryogenic engineering affect the design of superconducting magnet systems. The limits of Carnot (thermodynamic) efficiency require at least 80 watts of refrigeration power at room temperature to accommodate one watt at 4.2 K. In practice 2000 to 5000 watts (290 K)/watt (4.2 K) are required.[3] The cost of cryogenic refrigerators generally limits their availability to large and/or continuous use systems. To minimize the cost of cooling magnets to the liquid helium boiling point 4.2 K, especially the more massive ones, it is necessary that they be designed as effective heat exchangers in order to use not only the heat of vaporization but also the gas heat capacity of helium. The larger systems are always pre-cooled by liquid nitrogen (and sometimes by liquid hydrogen).

SUPERCONDUCTORS

The best superconducting material presently available (or under investigation) has limiting superconducting operating parameters of $T \leq 21°K$, $j \leq 10^7$ A/cm^2 and $H \leq 430$ kilogauss as shown in Figure 1. Of course these limits can not be achieved simultaneously. Though generally regarded as zero resistance conductors, some small but finite resistance seems to exist in all superconductors. The flux creep resistance described by Kim[4] is theoretically actual for all finite field and current combinations; and it is observable in those regions where it is within the range of state-of-the-art instrumentation. The flux flow resistance first described by Kim[5] is significant when a conductor is operated near its critical current. This rather

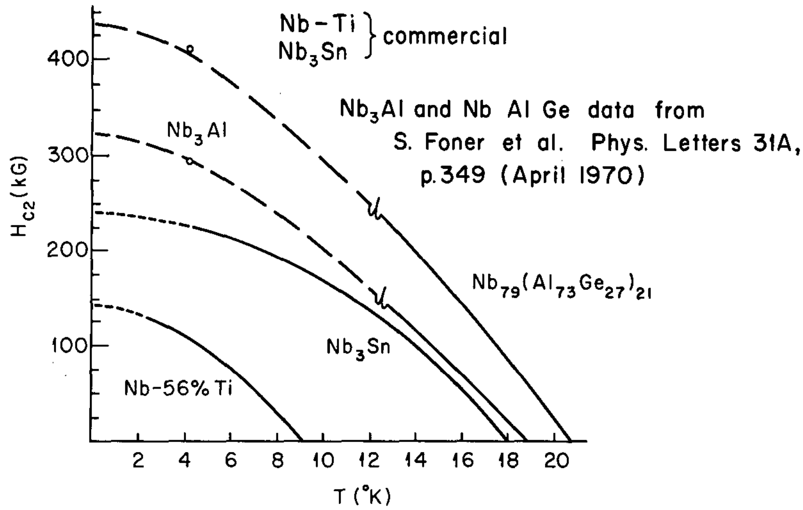


Fig. 1. Critical temperatures and fields of the most promising superconducting materials.

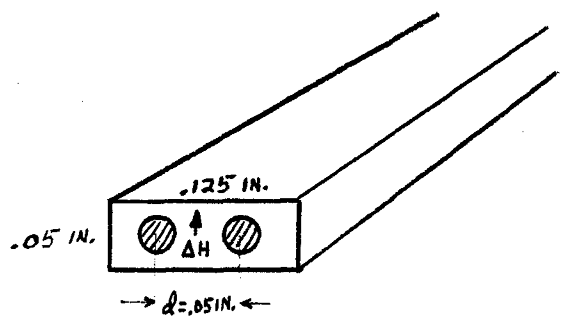


Figure 2 - Simplified NbTi Conductor

large resistance has been related to conductor stability by Gauster[6] and Coffey[7]. Other conductor resistances have recently been reported by Gilbert[8]. All these resistances and that due to conductor splice joints are important in the design of persistent mode magnets.

Commercial superconductors of two types are available. The brittle alloys (principally Nb_3Sn) are formed on thin metal foils which are soldered to dimensionally similar copper or aluminum stabilizing foils. The ribbon conductor is available in widths from 5 to 12.9 mm and in various thicknesses. The ductile alloys (principally NbTi) are available in a wider range of sizes and shapes varying from .08 mm to 50 mm, round, square and rectangular. NbTi development closely followed that of NbZr, the bare conductor experienced severe power density conditions which caused high temperature metallurgical changes, insulation damage, internal burn out and high voltage internal arcing. Consider a typical wire capability of 10^5 A/cm^2 at 30 to 40 kilogauss, with a normal state resistivity of 5×10^{-5} ohm-cm. When a section of conductor "goes normal," an instantaneous power density of $j^2\rho = 500,000$ watts/cc is present! In small magnets the current vanishes before damage is done; in more inductive magnets, the resultant damage is apparent.

To overcome this limitation and electrical instabilities the second breakthrough of the decade was achieved when Laverick[9] and Stekly[10] clad NbTi and NbZr in copper to increase electrical stability. This idea (like all great ideas, very obvious in retrospect) has led directly to the successful large magnets of today. Efforts toward higher current densities than were found possible with simple cladding led to multifilament NbTi conductor with as many as several hundred fine filaments imbedded in the copper matrix of a single wire (one such conductor has more than 400 NbTi filaments in a wire of only .02 mm diameter). The goal was to achieve ultimately the intrinsic stability predicted by Chester [11] and Wipf[12]. Unfortunately parasitic currents caused an additional instability.

Consider a typical conductor (Figure 2) simplified to two cores separated by d = 0.05 in. center-to-center.

Adiabatic Stability $\quad H_s^2 \le \dfrac{\pi^3 C J_c}{-\,dJ_c/dT} = \pi^3 C T_o$

dJ_c/dT

C

$J_c^2 w^2 \le \dfrac{\pi}{25} C T_o$

P. S. Swartz and C. P. Bean, 1965 and others

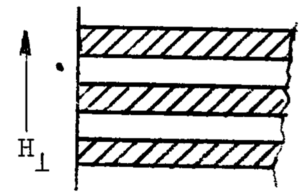
Intrinsic Stability of Thin Filaments (Twisted and Transposed)

P. F. Chester, 1967; P. E. Smith et al., 1968

Dynamic Stability $\quad \bar{D}_t > \bar{D}_m$

$$H_\perp^2 < \frac{\pi^4}{25}\frac{\bar{K}}{\bar{\rho}_f} T_o$$

H. R. Hart, 1968



$$H_\perp < \frac{4\pi\,\bar{h}}{10\bar{\rho}_f\,\bar{J}_c} T_o$$

Cryogenic Stability

- Cryostatic
  - linear
  - non-linear
- Cryodynamic

Fig. 3. Superconductor stability.

With a 4 in. length of conductor sample (~10 cm) the inductance between the two cores with opposite currents I_{loop} is [13]

$$L = 2 \times 10^{-9}\, \ell \left[\ln \frac{2\ell}{d} - 1 + \frac{d}{\ell} - \frac{1}{4}\frac{d^2}{\ell^2} + \cdots \right] = 8 \times 10^{-8} H$$

The approximate resistance experienced by the current I_{loop} is (assuming 5 kilogauss in the critical region)

$$R = \frac{\rho \ell}{A} = \frac{1.2 \times 10^{-8} \times 2 \times .05 \times 2.54}{.057 \times 2.54 \times 5} = 4 \times 10^{-9} \text{ ohm}$$

Therefore, the time constant is

$$\tau = \frac{L}{R} = \frac{8 \times 10^{-8}}{4 \times 10^{-9}} = 20 \text{ seconds}$$

Experimentally the time constant was found to be approximately 13 seconds for these conditions. In magnets the effective current loop can be hundreds or thousands of times longer and consequently parasitic current time constants of several years are possible.

The magnetic energy of the current loop in the short sample is $1/2\ LI^2$. Assume that this energy is quickly released and adiabatically absorbed by the copper substrate. The 10 cm sample weighs 3.6 grams (principally copper). To raise this mass by 5 K (to the critical temperature of about 9°K) would require 1.6×10^{-3} joules. Therefore, a loop current change of

$$\Delta\ I_{loop} = \sqrt{\frac{2W}{L}} = 200 \text{ AMPS}$$

would be sufficient to heat the superconductor to its critical temperature. A field change of only 3-5 kilogauss is sufficient to generate a loop current of 200 amperes.

One possible cause for the release of energy can be understood as follows: In one core the magnet current I_{mag} and the loop current I_{loop} are additive, in the other core the current differences $I_{mag} - I_{loop}$ is flowing. If the sum of magnet and loop currents exceeds the critical current I_c of one core, a transition to either the normal state or to the flux flow state will occur. In the first case, stored loop energy will be quickly released.

The third and last breakthrough of the decade was due to Smith[14] who showed that by twisting (or best transposing) the filaments of a

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conductor, rapid field penetration can be effected. The field penetration eliminates parasitic currents except in extreme cases of field change. This very significant conductor improvement has been employed in almost all high current density magnet designs subsequent to being reported. Since transposing filaments is not practical in extruded wire, small wires have been used in a "shoe-lace" braid configuration for rapid pulse superconducting magnets.[15] Transposing eliminates the last parasitic effect, that of the interfilament currents generated by the self field of a single conductor.

The various approaches to stabilizing superconductors can be generally broken down into three classes (Figure 3):

Adiabatic Stability - in which non-propagating flux jump activity is controlled by the proper selection of the shape of the parameter $j_c f$ (Temperature), the heat capacity of the superconductor and the superconductor dimensions; cooling is not required. Another form (not shown) includes the heat capacity of the stabilizing matrix.

Dynamic Stability - in which stabilizing material (copper or high purity aluminum) sufficiently damps the rate of field penetration that the resultant heat can escape harmlessly; generally used for Nb_3Sn, but also relevant to NbTi designs.

Cryogenic Stability - in which enough stabilizing material and cooling is provided to carry indefinitely the full magnet current if required; the method is the most stable available but is limited to current densities of about 5000 A/cm^2.

STRUCTURAL AND MECHANICAL ENGINEERING

In simple solenoids forces are of two types: expansive radial forces (hoop stress) due to axial magnetic field components; and compressive axial forces due to radial magnetic field components. In NbTi magnets the radial forces are usually borne by the NbTi, which has a yield strength of more than 100,000 PSI at 4.2 K and is relatively unaffected by the load. The axial forces are generally conveyed by soft copper with a yield strength of only about 15000 PSI at 4.2 K. Fortunately compressive yield usually only leads to some looseness in the magnet and is not destructive (though the split coil degradation effect was a case to the contrary in which axial loads caused turn-to-turn shortening). In Nb_3Sn magnets the superconductor is brittle and can not be used to restrain expansive forces. Therefore niobium, copper, beryllium-copper, aluminum and stainless steel are employed in various combinations.

Structural members are most frequently made of one of the 300 series stainless steels, with low carbon content to avoid brittle performance at cryogenic temperatures. To avoid magnetic distortions, structural materials are selected which exhibit no martensitic transformations or curie point transitions to 4.2 K. Some useful non-magnetic, ductile alloys are: 310 stainless steel with a 4.2 K yield strength of about 100,000 PSI, ARMCO 21-6-9 stainless steel with a yield strength of 195,000 PSI and a non-ferrous alloy MP35N with a yield strength of about 350,000 PSI.

A variety of insulation materials have been successfully incorporated into superconducting magnet systems, including teflon (for low stress areas), nylon, epoxy fiberglass, formvar and others. All except teflon have 4.2 K yield strengths over 50,000 PSI but are quite brittle.

Most coil systems require a careful stress analysis in the early design stages to identify areas requiring special structural support.

ELECTRICAL ENGINEERING

Calculation of magnetic fields, forces and inductances are generally conducted on electronic computers. While the magnetic field and stored energy generated by a specified distribution of current densities is invariant, it is possible to select large, high current conductors with lower inductance or small, low current conductors with higher inductance. The governing relation is

$$W = 1/2\ LI^2,$$

where W is energy in joules, L inductance in henries and I current in amperes. The selection of conductor current rating depends on the availability of power supplies generally.

A second consideration in the selection of current rating (or conductor size) of a magnet is the desired charge rate. The relation

$$di/dt = V/L$$

describes the coil terminal voltage-inductance ratio required for a specified rate of charge or discharge. The conductor size is also important in considering the protection of the magnet. To avoid internal damage due to arcing or thermal surges, an appropriate adjustment of coil parameters must be made, including conductor size, cooling, propagation time, internal shunts, insulation and current density.

The current density in various parts of a magnet is often varied to take advantage of the higher inherent current capability of superconductors at lower fields. However, increasing current density necessarily causes greater electrical instability, so current density grading must be cautiously applied.

STATE-OF-THE-ART MAGNET EXAMPLES

In the fast decade of the 60's nearly every possible magnet configuration has been adapted to superconducting designs: simple solenoids, split coil pairs, high homogeneity magnets, dipoles, quadrupoles, mirror quadrupoles and others.

Generally the magnets can be divided into two rather distinct classes: the very large, cryostatically stable magnets with low current densities and the smaller, less stable magnets with high current densities.

Some outstanding examples of the low current density magnets are the bubble chamber magnets already in operation and in various stages of design and construction:

Magnet	Diameter (Meters)	Kilogauss	Amperes	Megajoules	Completion
ANL	3.7	18	2200	80	In operation *
BNL	2.1	30	6000	70	Being modified
CERN	3.7	35	9000	750	1971
RHEL	1.5	70	7500	340	---
NAL	7.6	40	8500	~3500	1975

* See Figure 4

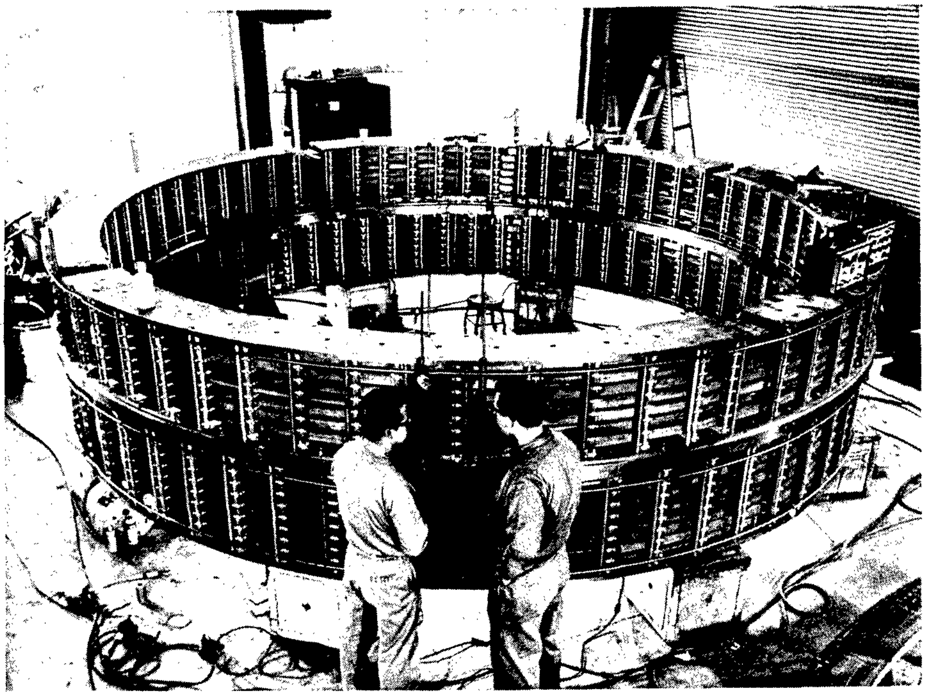


Fig. 4. The Argonne National Laboratory Bubble Chamber Magnet. The world's largest superconducting magnet.

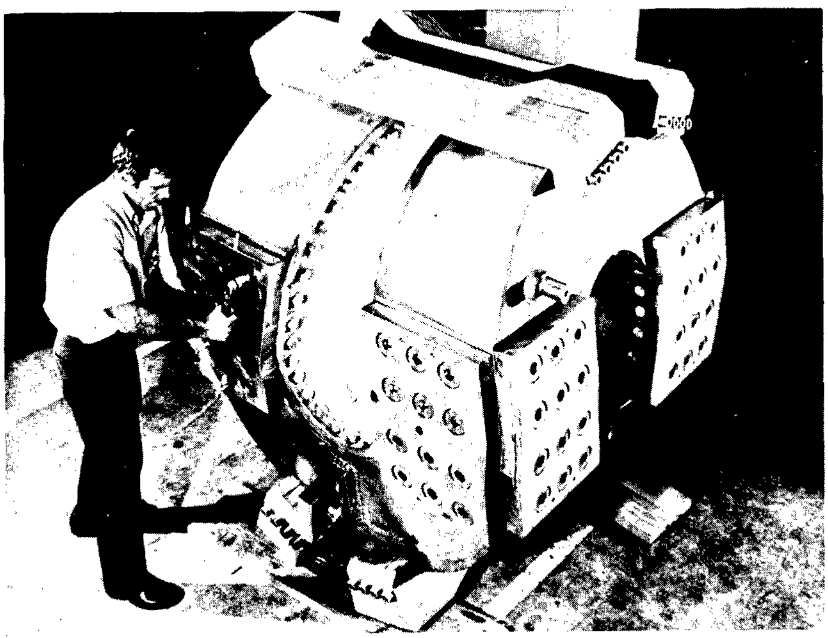


Fig. 5. Baseball II Magnet of Lawrence Radiation Laboratory, Livermore.

Another low current density design is the Baseball II minimum B magnet of Lawrence Radiation Laboratory at Livermore (Fig. 5). This magnet features conductor windings in a configuration like that of a baseball seam.

High current density have generally been for small magnets. A few notable exceptions are shown in Figures 6 through 8.

A 140 kilogauss, 6 inch bore Nb_3Sn magnet was built for NASA-Lewis Research Center by RCA (Figure 6). The magnet completed in 1967, remains the most spectacular achievement in high current density superconducting magnet design. It is unlikely that any magnetnet designer today would undertake to duplicate the feat. The magnet achieved its rated field with an average current density of 20000 amperes/cm^2. It has survived several high field normal state transitions with no apparent damage. The outside diameter of the magnet is 18.5 inches.

The Los Alamos Scientific Laboratory quadrupole-doublet (Figure 7) is an excellent example of twisted multifilament NbTi conductor use. This magnet provides a 6 inch bore with fields as high as 30 kilogauss on the conductor and a current density of 24000 amperes/cm^2. It incorporates a 500 ampere superconducting switch for long term low loss operation.

The very complex Oak Ridge National Laboratory mirror-quadrupole magnet system (Figure 8) employs both NbTi and Nb_3Sn. Peak magnetic fields of 85 kilogauss at 13500 amperes/cm^2 are experienced in this system. The massive structural members indicate the magnitude of electromagnetic forces which must be restrained.

APPLICATIONS

A wide variety of applications of superconducting magnets have been suggested and are in some stage of study or use; including:

1. Electron microscope optical system
2. Energy storage
3. Fusion physics research
4. High energy physics research
5. Levitation, rocket sleds and trains
6. Magnetic separators

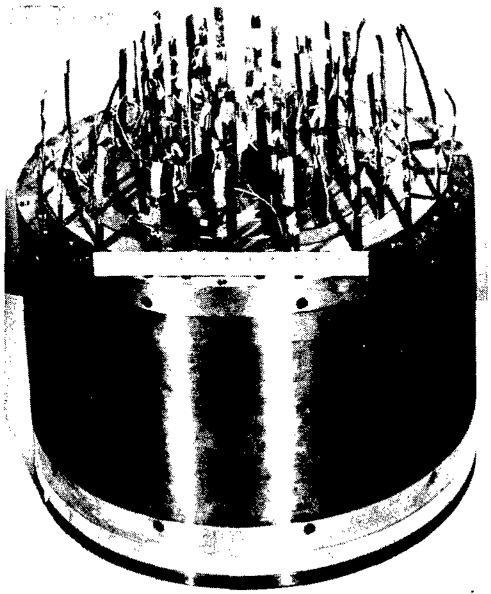
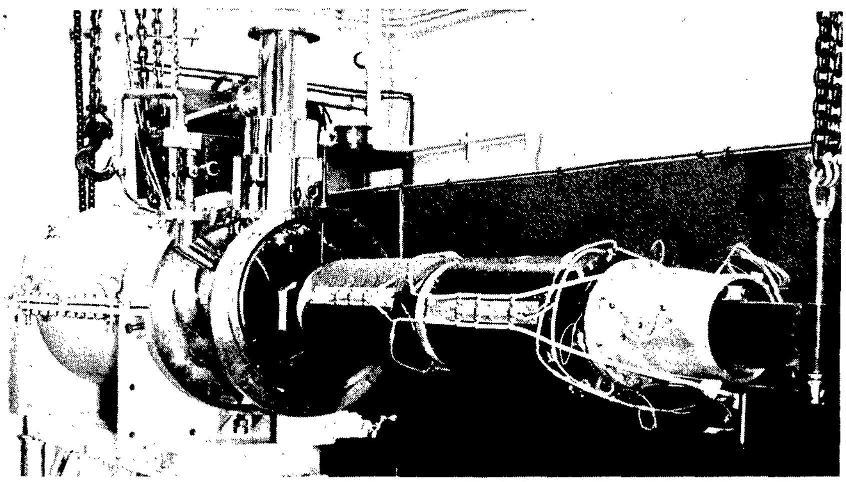


Figure 6

A 140 kilogauss, 6 inch bore Nb_3Sn magnet for NASA-Lewis Research Center by RCA

Figure 7

LASL Quadrupole doublet 6 inch bore NbTi magnet.



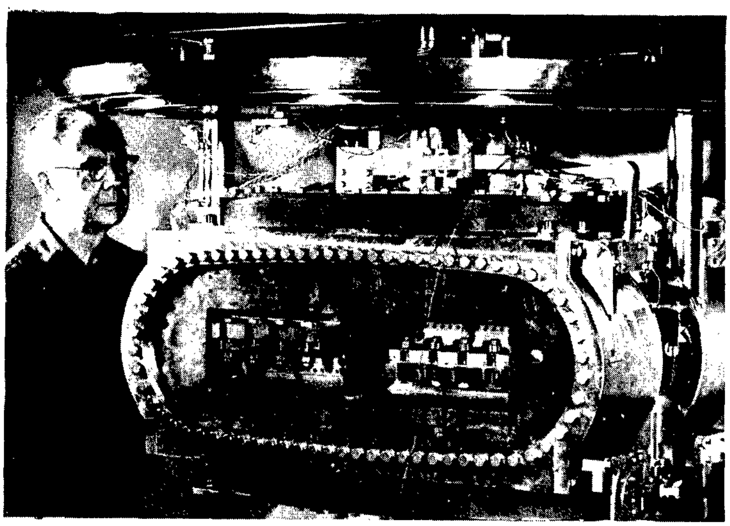


Figure 8

ORNL Mirror-quadrupole Nb_3Sn - NbTi magnet.

7. MHD energy converters
8. Masers
9. Motors and generators
10. Solid state physics research

CONCLUSION

Though adequate understanding is now at hand to engineer most magnet systems, several areas are still in need of study to provide for the magnet engineering requirements of the future. Superconducting materials require much more study to develop higher critical temperatures and higher critical fields. Twisted, filamentary Nb_3Sn needs development. The physics and metallurgy defining the behavior of superconductors in the critical flux flow region needs much more effort. Improved stability in high current density magnets awaits a more quantitative understanding of the energy sources in magnets, the inter-magnet interactions, the inter-conductor interactions, the inter-filament interactions, the high current density limitation, and the dynamic and intrinsic stability criteria. Magnet reliability would be improved by a more detailed understanding of normal state propagation times.

Superconducting magnets have moved from conception to operation in a remarkable short time period. Multimillion dollar superconducting magnet systems were in use less than 8 years after the Kunzler breakthrough; whereas the laser required 10 years from the laboratory to commercial production.

A number of obvious advantages of superconducting magnets have encouraged their rapid acceptance. These advantages include field intensity, field shapes, current densities, power supply simplicity, weight, size, cost, reliability and stability.

ACKNOWLEDGEMENTS

The helpful discussions with W. F. Gauster, M. A. Lubell and others is greatfully acknowledged. Appreciation is also expressed to Argonne National Laboratory (John Purcell), Lawrence Radiation Laboratory, Livermore (Carl Henning), Los Alamos Scientific Laboratory (John Rogers), Oak Ridge National Laboratory (Julian Dunlap) and RCA (Edward Schrader) for photos.

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SESSION C

Wednesday Afternoon, 4 November 1970

Chairman: F.B. Isakson
Office of Naval Research

SUBMILLIMETER JOSEPHSON EFFECT DEVICES*

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Abstract

The extremely non-linear character of the Josephson effect--tunneling between superconductors--has led to its use as a detector, mixer and frequency converter at wavelengths extending into the submillimeter range. Although their development is still at a rudimentary level, Josephson effect devices already compare favorably in terms of sensitivity, frequency response and speed with other submillimeter detectors. Present knowledge of the nature of the Josephson effect permits reasonable projections to be made for realizable sensitivities in various modes of operation and suggests additional functions for Josephson effect devices in the submillimeter region.

* Supported by the Office of Naval Research under Contract number N0014-67-A-0398-0003.

In looking over the program for this Workshop I was impressed by how close so many applications of superconductivity are to being put to serious practical use. By and large, as I read it, most of the work discussed at this meeting must be taken very seriously by those of you concerned with deciding what the Navy will be using to carry out various tasks in the years just ahead. After all, superconducting motors and other types of superconducting rotating machinery are already in operation. Other large scale applications are being actively developed such as the superconducting linear accelerator. Even the Josephson effect, in the form of magnetometers, is in use in commercially available instruments. So it is that the subject of my talk, "Submillimeter Wave Josephson Effect Devices", is something of a maverick, or is it Pinto this year?

Well, what I have to talk about is certainly not going to go into the very next generation of naval systems. Our time scale is maybe 5 years to commercially available "instruments"; maybe by the end of the seventies, we'll be seeing how we can incorporate these devices into various kinds of systems. So, I have both a certain freedom to indulge in optimistic prognostication, and yet a certain burden to convey to you something of our excitement about the use of Josephson effect devices at high frequencies -- why we think that in some respects they really are something new under the sun. It is perhaps appropriate here to recall that superconductivity has been with us since 1911 (or at least has been around, not necessarily with us!) but the Josephson effect only since 1962.[1][2] Some of what I have to say may be pretty heavy going; there is in fact much that is unclear still about some of the fundamentals of these devices. What I hope you will carry away from my talk is a general awareness of expectation - that some of us in the midst of the flak really believe we're onto something - and also, some appreciation of the complexity that we face in converting interesting phenomena into functioning hardware.

Just what is it that has gotten those of us directly involved, excited about these high frequency Josephson effect devices? It was just over three years ago that the first report of the use of the Josephson effect as a far-infrared detector appeared in print[3] and it was only about two years ago that numbers characterizing the device in terms of such things as sensitivity, frequency response, and time constant, or speed of response, saw themselves immortalized via the printed page.[4] Yet those first crude measurements already yielded numbers that were comparable to the best of existing helium temperature cooled far-infrared detectors.[5] So, let me start by giving those numbers and the comparison numbers for the best other detectors.

In Table I we're restricting ourselves then to helium temperature far-infrared detectors and the first set of numbers I want to talk about refer to spectral range -- over what range of wavelengths can one use the detectors? The Josephson effect detectors using niobium as the superconducting material have been operated over the range from long wavelengths to wavelengths as short as 250 microns. The short wavelength limit depends upon the superconducting material. Materials with larger superconducting energy gaps, the parameter Δ that was spoken about this moring, will enable us to extend the short wavelength limit from the 250 microns (see Table I) for the niobium detector to shorter wavelengths. With a material such as niobium nitride, material that is being worked on in several laboratories, we might reasonably expect to go to wavelengths as short as ten microns. If we do then we will be covering the full range that is typically covered by one or another of the doped germanium bolometers.

The next set of numbers I want to talk about represent the time constant -- how fast the device responds. The Josephson effect device has been measured in terms of simply setting a lower limit. It is certainly faster than 10^{-8} seconds, a number established by actual measurement.[4] How fast it is remains to be seen. We expect not to run into any fundamental limit until we are at a time roughly given by the inverse of the energy gap parameter Δ, and that means a time on the order of 10^{-13} seconds or so. What about competitive bolometers or detectors? About the best time constant that I could find was 3×10^{-7} seconds for the so-called indium antimonide electron bolometer.

What about sensitivity, -- the third of the three characterestic numbers I want to present to you? Sensitivity for our purposes can best be compared by using the concept of noise equivalent power[5]-- exactly what that is and how it is obtained from various experimental setups is not terribly important for our purposes. The numbers given will be expressed in terms of watts. For the Josephson effect device operating in what I call the video mode, and I will be explaining what that term means as we go along, has been measured[4] to have a noise equivalent power of less than 5×10^{-13} watts.

TABLE I

HELIUM TEMPERATURE FAR I.R. DETECTION

<u>Spectral Range</u>

Josephson Effect	:	250 - 10,000 microns
Doped Ge Bolometer	:	10 - 1,000 microns

<u>Time Constant</u>

Josephson Effect	:	less than 10^{-8} seconds
InSb Electron Bolometer	:	3×10^{-7} seconds

<u>Noise Equivalent Power</u> (NEP) (WATTS)

Josephson Effect	:	5×10^{-13} (Video Mode)
		5×10^{-15} (Regenerative Mode)
Others	:	5×10^{-13}

Operating in still another mode, which I'll call the regenerative mode,[(6)] this number has been improved by two orders of magnitude. The smaller the number in terms of watts the better your detector. Competitive detectors? With both the doped germanium series and the indium antimonide electron bolometer series under certain conditions, and not necessarily with any particular one of those types, NEP's on the order of 5×10^{-13} watts have been reported. The numbers given here are useful and can be taken as indicative when used to compare one detector to another. I do not wish you to take too seriously the actual magnitude of this number in terms of watts. The reason is that the numbers quoted here are obtained as extrapolations and are meant to refer to certain standard conditions of device operation, although of course, we always are taking measurements with respect to some system or other, and generally speaking, the systems that are involved are poor. So these numbers are not to be considered as indicative of what you can achieve in a system but rather are useful here for comparative purposes only.

Most of the work on Josephson effect detectors has used a point-contact form of the junction. You've seen it before and I'm going to show it again. Fig. 1(D) shows the point-contact form of junction where a fine tip formed from a superconducting wire of one material, for instance niobium, which is one very frequently used, is pressed very gently against another piece of superconductor which could also be niobium, or it could be something else, e.g., it could be lead. The key region is the region of the constriction. The constriction forms a barrier to current flow, which is the key idea here. You are concerned with passing current from one essentially bulk superconductor to another essentially bulk superconductor through some kind of a barrier which in the point contact is this very tiny constriction. There are other possible modes that can be used or have been used to show the Josephson effects. Look at Fig. 1(A) for instance. Here is the classic thin-film type of junction you have two essentially bulk pieces of material separated by a real physical dielectric barrier, 10, 20, 30 and sometimes even 100 angstroms of material. Yet you can pass current from one superconducting film to the other through this material. That current is the Josephson current and I want to turn now to a discussion of it.

I am going to refer to the Josephson current as it depends on a whole variety of variables. A few of them are temperature, magnetic field, voltage, time, and even space variables by which I

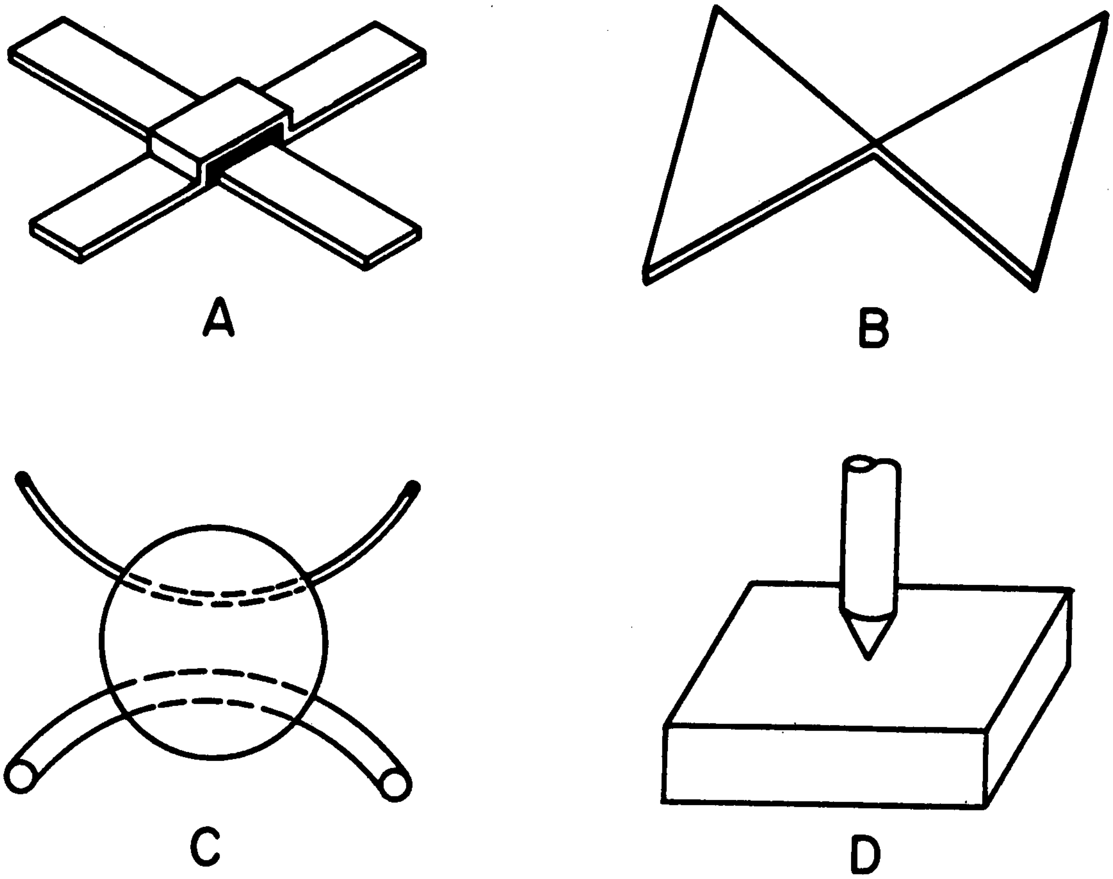

Fig. 1 : Several different forms of Josephson junctions.

mean position in the barrier. I want here, today, to concentrate my attention to the dependence of the Josephson current on two parameters, the voltage and the time. We are fortunate in having a phenomenological theory[2] -- an intermediate theory -- that enables us to express the results of many -- and in some cases very complicated -- experiments in reasonably simple terms. Terms, at least, that are far simpler than would be required if we had to go back each time to the basic microscopic quantum-mechanical theory.[1][7] So, I want now to talk very briefly about this phenomenological theory and see what some of these expressions that we work with all the time are, and how we can in fact use them to learn something about the Josephson current. In the phenomenological theory the Josephson current is written in parametric form. That is, we do not write it directly in terms of a voltage and time, the two variables that I am concerned with here, but we write it first in terms of some other parameter which I will label φ: $I_J = I_J(\varphi)$. Then we express the parameter φ and relate it to the variables of interest, namely, the voltage and the time: $\varphi = \varphi(V, t)$. The theory tells us how to write all of that -- you have seen the equations before -- but it doesn't hurt to see them again. The first equation relates the Josephson current in a non-linear way to the parameter φ via a sine function of the parameter φ:

$$I_J = I^{\circ}_J \sin \varphi \; (V, t).$$

φ now depends upon the voltage and time and that is expressed in a simple differential equation of the form

$$\frac{d\varphi}{dt} = \frac{2e}{\hbar} V.$$

Let's look at some consequences of these equations. Suppose the total voltage across our junction, whatever form it is, is zero. We have a zero voltage case. Then the parameter φ is a constant. The amount of Josephson current that is flowing under any given set of circumstances will, under these conditions, at zero voltage, be determined by your external circuit. How much do you want to drive through the junction? But, there is a limit to this, and the limit is that we cannot drive more than a certain maximum amount which is written as I°_J in my way of presenting it. If you exceed this amount you will switch out of the zero-voltage state. You will leave the regime of the dc Josephson effect -- finite current at zero voltage -- and you will pass into a new regime where there is a finite voltage across the junction. Let's look at that regime and see what our equations tell us. If now the voltage is set equal to some constant dc amount, the parameter φ varies directly with time. For $V = V_{dc}$, $\varphi = (\frac{2e}{\hbar} V_{dc})t$. It increases as time increases and the current, in consequence, will vary as the sine of this parameter and hence has a sinusoidal variation in time: $I_J = I^{\circ}_J \sin(\omega_J t)$ where $\omega_J = \frac{2e}{\hbar} V_{dc}$. The frequency of this sinusoidal variation is directly proportional to the voltage bias. This then is the ac Josephson effect where a dc voltage across the junction causes an alternating Josephson current to flow. The Josephson frequency at which this alternating current flows, ω_J, is proportional to the dc voltage and the number that indicates the frequency-voltage relationship is 1 mV = 483.6GHz.

The next thing we want to do is to see how one can use this to detect radiation. The simplest thing to ask is "What happens if we now bias our junction at some point and we apply a single frequency radiation to the junction?" In that case we have for the total voltage across the junction a dc term as before, plus now an rf voltage that is varying at some rf frequency ω_{rf}: $V = V_{dc} + V_{rf} \cos(\omega_{rf}t)$. The amplitude of this variation depends upon the amount of rf but the variation itself is at a frequency ω_{rf}. The result is that φ becomes: $\varphi = \omega_J t + (2e/\hbar)(V_{rf}/\omega_{rf}) \sin(\omega_{rf}t)$. Without actually writing down the expression for the current, which is rather complicated and not terribly important for our purposes, I think you can see that the Josephson current is no longer at a single frequency but is, rather, frequency modulated. ω_J would be the frequency at which it would oscillate if we had only the dc bias, but now we have a frequency-modulation term whose amplitude depends upon the amount of rf across the junction. If you have any frequency-modulation situation, as here for a Josephson junction or for your home or car fm radio, then side bands appear in the problem.

In the Josephson problem the side bands are at the frequencies $\omega_J \pm n\omega_{rf}$, that is, the simple sum and difference frequency side bands related to the two frequencies that we started out with. The number n is possible here because we can also have side bands that come about from the mixing, as it were, of the Josephson frequency and harmonics of the applied rf, the number n being an integer, 1, 2, etc. These are quite visible and they are visible because of the extreme non-linearity of the Josephson relationships. I will talk later about these side bands at some finite frequency. They represent what I would prefer to call an active mode of behavior of the device. As we go along I will be using such words as heterodyne mode, self-mixing, frequency conversion -- all of them are involved with the simple sum and difference behavior between the Josephson frequency (which we have <u>not</u> applied -- all we have done to get this is to put a dc bias on the junction) and the single applied rf frequency in the problem. In a practical scheme the single rf frequency could be a signal that we might want to detect. I will be saying quite a bit about that

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later, but first I want to go back and present a bit more information that enables us to talk about the video and regenerative modes of the far-infrared broad-band detectors that I started with.

The first thing I want you to notice is that since the side bands occur at particular frequencies, and since the ω_J is proportional to the dc voltage, that by setting the dc voltage at some discreet value, corresponding to whatever the particular value of n one happens to have chosen, say n = 1, the one side band is pushed down to zero frequency. Well, what is that? That is dc. The condition is $V_{dc} = \frac{n\hbar\ \omega_{rf}}{2e}$. That means that we expect a change in the current that is flowing at the bias V_{dc}. This, then, is what we are going to say. We put on some rf and because of this relationship at certain discreet points in the I-V curve depending upon the number n and the rf applied we expect to see change in the current that flows in the dc V-I curve.

Now, let's take a look at it and see what it looks like in Fig. 2. Here we see the junction voltage versus the junction current for a niobium - niobium point-contact junction maintained at a temperature of 4.2°K. In the curve labelled "-MAX", taken in the absence of applied rf, we clearly see the zero-voltage current, current flowing at zero voltage, and then when we have exceeded the maximum zero-voltage current corresponding to the dc Josephson effect, we get on to a finite voltage part of the curve. As we apply increasing amounts of rf power we see characteristic current steps arising in the V-I curve at various particular biases corresponding to the applied rf, which, in this case, is at 72 GHz. For instance we see a step labelled number 1 that corresponds with the integer n = 1, another step for n = 2, another step for n = 3. If you look across the figure horizontally, then you can see that the amplitude of the current that flows at a particular bias, these sensitive bias points, is a function of the amount of rf power incident on the junction, so in a sense we already have a detector when we are able to see a curve of this sort.

To use this for broad band purposes, in which you do not have only one rf frequency incident on the junction at one time, but rather a whole band of frequencies, note that the rf power also modifies, it actually decreases, at least initially, the amount of current that can flow at zero voltage. At zero voltage the number n measuring the steps corresponds to n = 0. That simply says that all frequencies affect the zero-voltage current in the same way. They all tend to decrease the zero-voltage current. So we will have a device that is

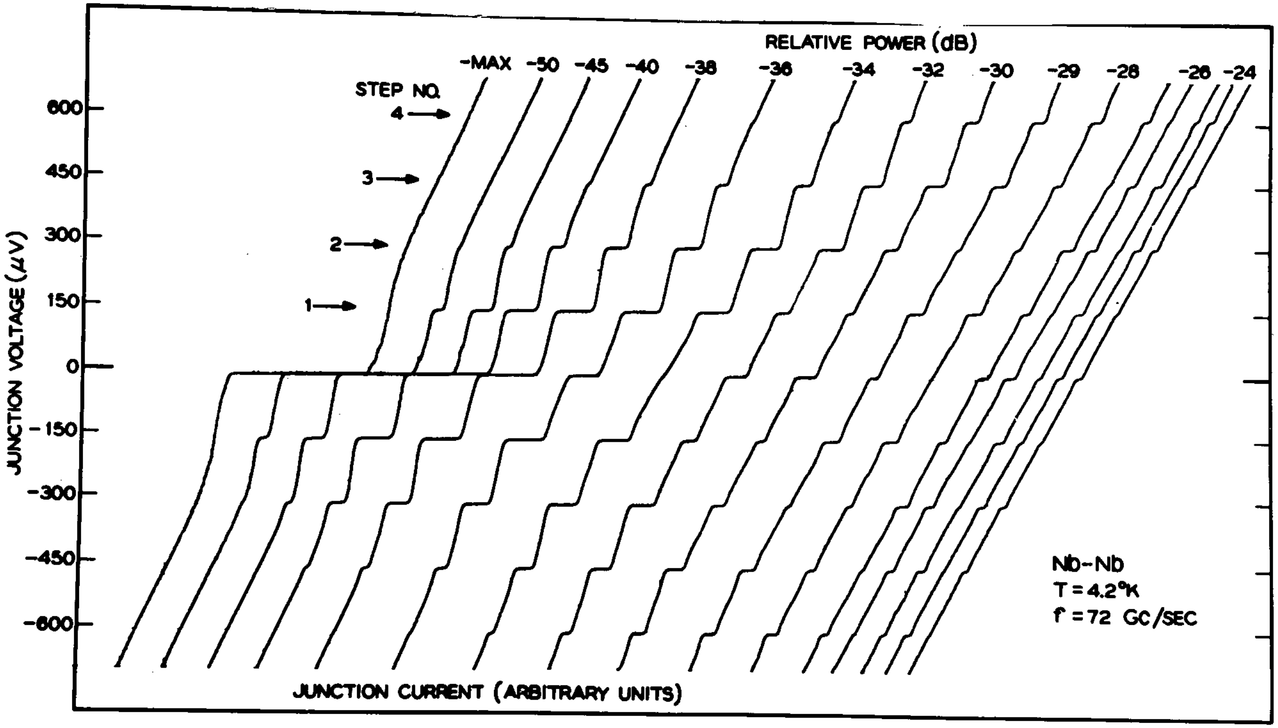

Fig. 2: V-I curves for a Nb-Nb point-contact junction showing rf-induced constant-voltage steps.

sensitive to any frequency provided we are able to measure, sensitively, a change not in the zero-voltage current but in the maximum amount of zero-voltage current. That is a little bit of a twist in the problem that makes life a little difficult but then it makes it a little fun too. So what we have to do then is to concoct a system where we can expose our junction to a wide band of frequencies and develop a scheme for measuring a small change in the maximum amplitude of the zero-voltage current under these conditions.

Next, we will consider Fig. 3, which is of a remarkably crude system, but one that works, and was used in fact, to obtain the number that is quoted in Table I under NEP. This is the system that operates in what I called the video mode, the mode where we examine the change in the maximum amplitude of the zero-voltage current. We have a light source some place. The radiation comes down some kind of a pipe, a light pipe, and it falls on a junction. We have indicated a point contact schematically. Of course, the whole thing is maintained in a cryogenic environment of one sort or another. We provide junction bias and this enables us to develop a scheme[4][8] which I won't go into for extracting the signal for actually measuring the change in zero-voltage current. We use ac techniques by providing a light chopper at some small frequency, (it doesn't matter -- one hundred cycles or whatever is convenient) -- in which case one obtains an ac signal to feed into a pre-amplifier. Following phase-sensitive detection the output is plotted on a recorder. Now what we get out on the recorder depends on a number of things. Let me talk about just a few.

It depends, of course, on temperature. For most of the experiments you can work at 4.2° if the junction were of niobium. What happens if you were to work nearer the transition temperature? There are dependencies of critical currents on temperature. They are known rather well. The important thing for present purposes is for me to remark simply that if you operate at roughly one-half of the critical temperature the sensitivity of what you get out to small changes in temperature is essentially zero.

More important in determining the amplitude of your signal is how much of the radiation coming down the light pipe effectively couples to your junction. This then is one reason for using a high impedance point contact. We get more rf voltage across a high impedance junction for a given amount of power down the pipe. If we were able to improve the coupling scheme then we would get more signal out for a given amount of power coming down the pipe. The third point I want to mention is that what we see on the recorder depends very sensitively on how effective you are in extracting the signal. The smaller the change in zero-voltage current that you can measure, then the larger will your signal be for a given amount of power coupled into the junction.

There is one other way that we can improve the situation and this leads to the so-called regenerative mode of operation. I remind you that the very simple system of Fig. 3 -- light pipe, junction, amplifiers -- constitutes the video mode of operation. Now let me show you what you have to do to get to the so-called regenerative mode.[6] You pay a little bit of a price in terms of broad-bandedness and you modify the environment in the area of the junction. You modify it in such a way as to make some kind of reasonably low Q resonator coupled to the junction. Several examples are given in Fig. 4. When you do this, and I will be explaining this a little bit later, you get a feedback type of interaction between the relatively low Q resonator and the junction. The feedback type causes an enhancement in the response of the junction to radiation within the band pass of the resonator and this leads to more signal out for a given amount of power in, that is, improved sensitivity. It is such a resonator-coupled structure that leads to the number 5×10^{-15} watts for NEP that I spoke about earlier for the regenerative mode.

Now, essentially, this is all I want to say about the broad-band far-infrared detectors. I want to go on now and talk about what you can do to improve and to enhance and to work with the active mode, the heterodyne mode, the frequency conversion mode, where we are dealing with essentially monochromatic single frequency input. Again, the key idea is to use a resonator. Here it is not necessarily required that you make it low Q because we expect to be dealing with essentially monochromatic input. I am going to show you Fig. 5, which is not the best design of such a system, but it is one that we have used.[9] We have again, out of niobium, a Josephson junction. The junction now forms an essential part of the resonator circuit, which is a coaxial cavity, that happens in this case which we have used for a series of experiments, to resonate at a frequency of 20 GHz. This is about one centimeter wavelength. I would like you to think of the cavity as an impedance transformer. It transforms what is usually a very low impedance at these high frequencies connected with the Josephson

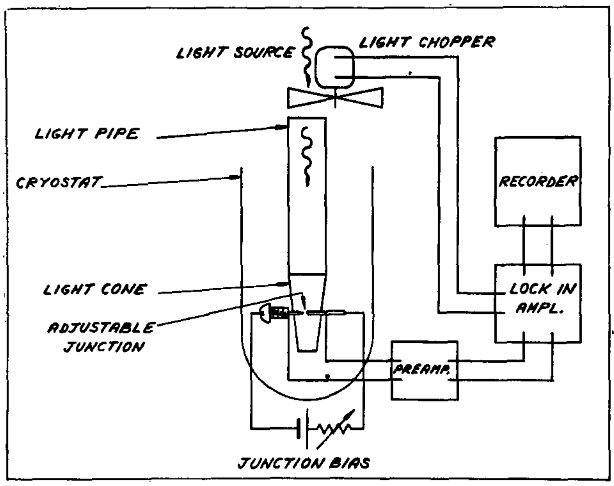

Fig. 3: Sketch of simple system used as Josephson effect far-infrared detector.

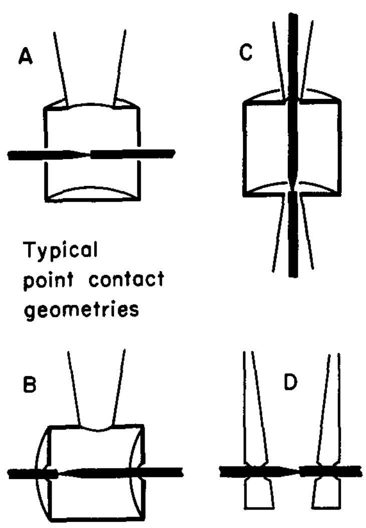

Fig. 4: Several different forms of junction-cavity coupling scheme for use as regenerative detectors.

20 GHz Coaxial Cavity

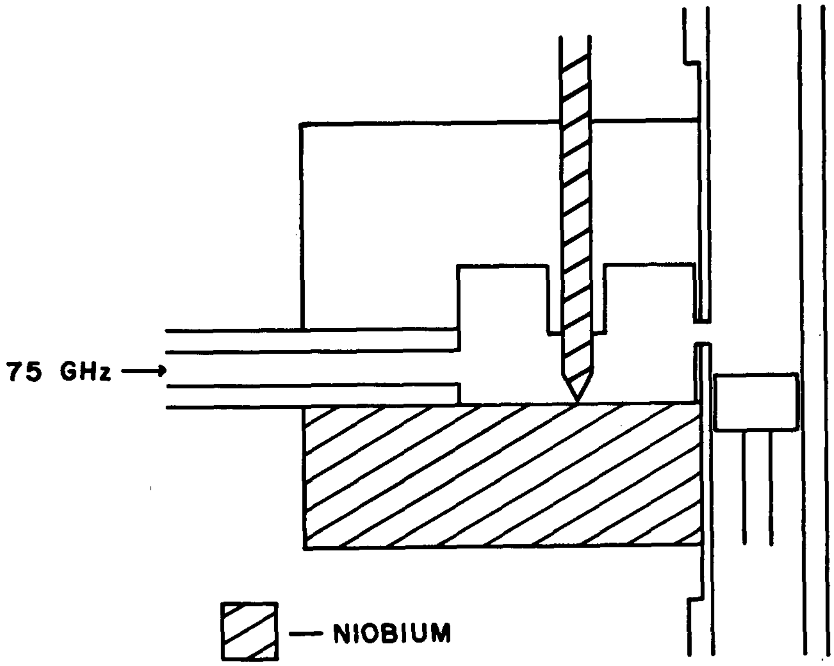

Fig. 5: One form of junction-cavity coupling used in frequency conversion experiments.

junction into a matching high impedance which we are forced to work with in terms of output waveguide at such frequencies. The cavity then is an impedance transformer. The rf fields in the cavity will have low impedance points where we put the junction, they will have high impedance points where we couple to the relatively high impedance output waveguide.

In order to make a detector we have to feed the signal in. In Fig. 5 we have indicated a signal input of 75 GHz coming down a small 4 millimeter wavelength type waveguide and in order to do the job properly, we should of course impedance transform also at this signal frequency. Not only at what will turn out to be the output frequency, the cavity frequency, but we should also impedance transform at the input frequency. Our purpose in making this system and in studying it was not to make an infrared detector, but rather to study the mechanism of frequency conversion or heterodyne self-mixing. We got around the matching problem, at least on the input, simply by ignoring it and cutting a small hole in the co-axial cavity to send our radiation in. Of course, you take an enormous shellacking in terms of how much power is in the waveguide compared to how much of the 75 GHz you can get down effectively coupled to the point, but no matter. We are able to do the experiment and explore and investigate the mechanism of operation which at this stage comes first.

Let me say a few words then about the effect of coupling the resonator to the junction. If there are rf currents, flowing across the junction, at the frequency corresponding to the surrounding structure, in this case the co-axial cavity at 20 GHz, then those ac currents will serve to excite the resonant mode of the cavity.[10] They will, in other words, tend to excite the cavity and build up rf fields in the cavity. Those rf fields in turn will act somewhat as though we had applied radiation at the cavity frequency. That is, in terms of its effect on the junction dc V-I characteristic, the radiation field that is excited and grows and builds up in the cavity will feed back on the junction and produce a change in the dc V-I characteristic at that bias which maintains ac currents of this frequency in the junction.

Lets take a look at the V-I curve in Fig. 6 and see what we can see. You notice a little bit of a step in current, at about 50 microvolts. It is very similar to the steps we saw before when we actually applied an rf signal. Here, I emphasize, we are not applying anything. All we have done is to put the appropriate dc voltage

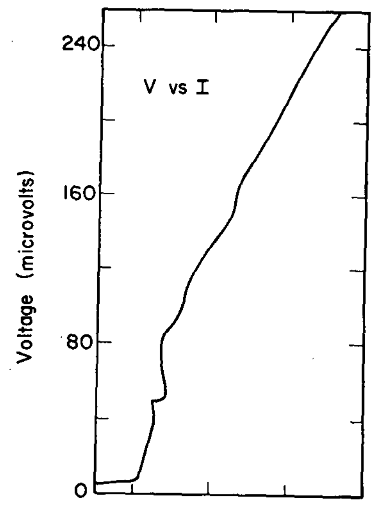

Fig. 6: V-I curve for junction coupled to co-axial cavity as in Fig. 5 showing small constant-voltage step at bias such that Josephson frequency equals cavity frequency.

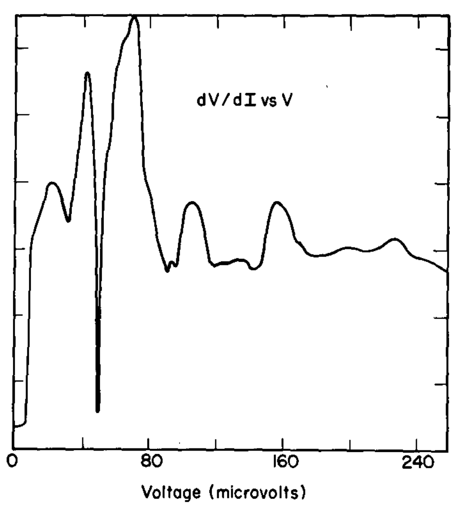

Fig. 7: Data of Fig. 6 presented as junction resistance, dV/dI, versus voltage. Constant-voltage step appears as a sharp drop in resistance.

across the junction so that the Josephson frequency at the bias point is equal to the resonant frequency of the cavity. Sometimes it is better to look at little steps and make them appear big and so we frequently use a different technique[11] which is to plot, not the voltage versus the current, but rather the dynamic resistance across the junction versus the dc voltage bias as in Fig. 7. When you do that, little steps in current turn out to be very strong drops in resistance and so here you see a very strong drop at a voltage where the Josephson frequency matches the resonant frequency of the cavity. What happens now if we put on some rf? Well, we know some of what is going on as is shown in Fig. 8. We have the same voltage scales, and the same junction as in Figs. 6 and 7. Here again is the little step ("C") due to the regenerative or feedback interaction of the cavity on the junction. There is a big step (corresponding to the steps we saw before with n = 1) for the applied frequency of about 75 gigahertz ("rf"). What is new in this case are the two additional little steps labelled "s" and "d". These steps were not present before when we looked at the effect of rf alone. They were not present before when we looked at the effect of the cavity alone. They arise from the active, or Josephson, self-mixing mode of operation. They come in at step "d" when the Josephson frequency is equal to the difference between the applied rf and the cavity frequency, and at step "s" when the Josephson frequency is equal to the sum of the applied rf and the cavity frequency. Again, I emphasize, there is only one applied frequency, the rf, the signal.

Let's look at it in terms of the resistance curve in Fig. 9. "C" labels the very sharp drop in resistance that we had earlier for the cavity alone. "rf" labels the very sharp drop in resistance that we had earlier for the rf step alone, and "d" and "s" label the two drops in resistance that now are saying something new. Let me explain again what happens. Suppose we are biased at "d". Here, the Josephson frequency mixes with the applied rf to produce a side band that is equal to the cavity frequency. That is, current at the cavity frequency is flowing in the junction! Since there is current flowing in the junction at the cavity frequency we expect to see a current step and hence a sharp drop in resistance where we are biased at "d". Similarly, at "s" we have the Josephson frequency mixing with the applied rf and producing a side band again at the resonant frequency of the cavity. So we have a heterodyne situation where the dc bias via the Josephson junction plays the role of the local oscillator. The only frequency coming in is the signal frequency -- the applied rf.

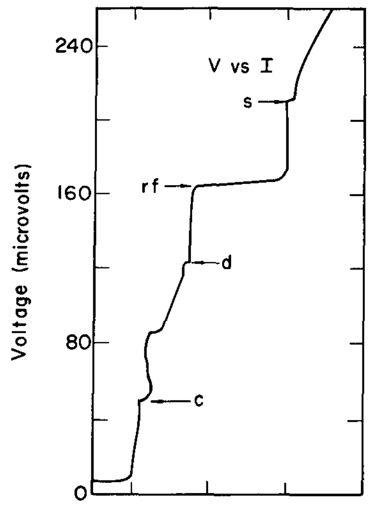

Fig. 8: V-I curve for the same junction-cavity system as for Figs. 6 and 7 showing the effect of applied rf at 75 GHz. Constant-voltage steps are visible corresponding to cavity ("c") and applied rf ("rf") frequencies, and to their sum ("s") and difference ("d") frequencies.

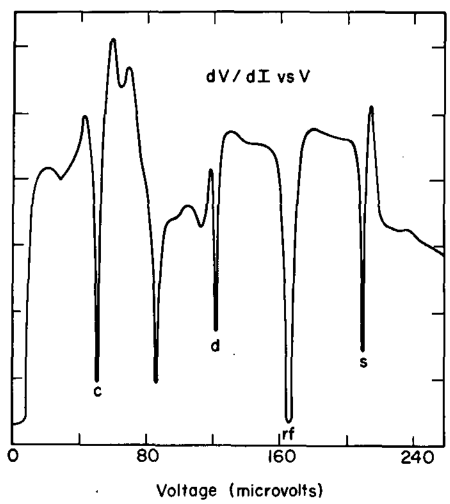

Fig. 9: Data of Fig. 8 presented as junction resistance, dV/dI, versus voltage. Constant-voltage steps appear as sharp drops in resistance.

The only frequency coming out is the output frequency to which we have matched our output waveguide via the impedance transformer of the resonant cavity.

These data were taken with a relatively small amount of input signal -- i.e., applied rf. If we increase the rf power then we will also see in the V-I curve not only steps corresponding to n = 1 but n = 2, 3, 4 etc. and correspondingly around each of those steps there will be very high voltage bias conditions where the mixing product between the high Josephson frequency and the harmonic of the applied rf excites the cavity resonance. Again we see these little steps and we have seen them out to n = 6.

Although in the above situation, the output frequency is at a lower frequency than the input, we can also run this experiment in reverse. The junction cares not. We have in fact done this using a tiny resonant stub coupled to our junction.[9] The stub was resonant at a frequency of about 500 GHz. In that case our signal corresponded to 25 GHz and again we were able to see the sum and difference steps telling us that the Josephson junction was converting the input low frequency signal into the output at 500 GHz exciting the resonator.

The next thing that remains to be done is no longer to look simply at the dc V-I characteristic but rather to look directly at what is coming out the output waveguide and we will be doing that over the next several months.

Finally, let me close by telling you about some of the other work that I think is necessary and will be undertaken as time goes on. (see Table II). The first area where I feel that future work will be very important is in providing junctions of different materials. This is important for two reasons. The first is, as I mentioned way at the beginning, the higher the energy gap parameter, the shorter the wavelength at which our devices will operate. I want to emphasize here that a given junction that operates at a short wavelength also is good for all longer wavelengths. This is in stark contrast to many of the conventional bolometric infrared detectors where you have to tune them for the various wavelengths. A second important characteristic that we look to junctions formed of new materials to solve for us is that their higher T_c implies that we can operate perhaps as high as 8 to 10°K. This is important because it is in that temperature range where relatively economical closed-cycle helium refrigerators

TABLE II

FUTURE WORK

(1) Junctions of Different Materials:

(a) Higher Δ => Shorter wavelength.
(b) Higher T_c => 8 -10°K operation

(2) Junction Design:

(a) Stable, reliable, reproducible
(b) Coupling of signal Δ I F to junction

(3) Signal Processing:

(a) Superconducting circuits for IF or second IF amplifiers
(b) Signal "extraction" for broad band use.

are available for field use.

The second area where I believe future work will occur is in the area that I have labelled junction design. Again there are two reasons here, some of which you have heard. We need to have stable reliable and reproducible junctions. Point contacts are fine for the laboratory and for telling us that "yes indeed there is something there worth working for," but we need to solve the field operational problems involved in these three key words and that will come about with further work on junction design. Again we need to work much harder than has been done so far on the problems of coupling the signal to the junction effectively and coupling the output, or the rf, out of the junction effectively.

Finally, the third area, which I have called signal processing, again consists of two parts. In order to minimize the noise that the junction sees, we simply have to get away from having it see, even remotely, room temperature circuitry. We need to involve superconducting circuits for the post-junction stages, either first or second or perhaps both IF stages in terms of a super-heterodyne as opposed to a heterodyne system. At last, to close out, referring once again back to the broad-band use which will always remain with us, new modes of signal extraction need to be investigated in order to increase the sensitivity for broad-band use.

The paper is now open for questions.

Name of questioner not discernable. The question was "Do I have any idea about the cross section at the junction?" No, I don't. There are measurements that have been made by a variety of techniques and people have put numbers on this and they speak in terms of effective radii of about 100 Angstroms. Take it for what its worth.

Watt Webb: "Is there any kind of a fundamental limit to the sensitivity of these devices in the infrared frequencies?"

Dr. Shapiro: I believe that kT at 1° corresponds to something like 10^{-20} watts. Is that it? It's really quite a low number. Far lower than we have talked about here and for X-band radars with large enough antennas and all this sort of thing working in heterodyne modes, people quite commonly measure powers in this 10^{-20} region. Now that is at X-band. It's not in the far infrared. My own belief is that ultimately, we ought to be able to get essentially photon counting performance out of these detectors. But that is a long way off.

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MAGNETIC FIELD MEASUREMENTS USING SUPERCONDUCTING AND CONVENTIONAL DEVICES

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INTRODUCTION

The principle objective of this paper is to discuss the operation, performance and utility of superconducting magnetometers as well as the more conventional proton precession and optically pumped magnetometers. An elementary discussion of the physics of each of these magnetometers will be given first. Then, the performance characteristics and specifications will be reviewed with emphasis placed on unique features of each magnetometer.

SUPERCONDUCTING MAGNETOMETERS

Many different types of magnetometers have been constructed using various properties of the superconductive state. The earliest magnetometers used the flux exclusion property (the Meissner-Ochsenfeld effect) of superconductors. This device lacked sensitivity and response time (10^{-6} gauss resolution and 10 kHz maximum operating frequency). The experimental verification of quantized magnetic flux in 1962 led to considerable effort in the direct use of the flux quantum as a magnetometer with analog as well as digital response. Operating speeds as high as 100 kHz were achieved with field resolutions of 10^{-7} gauss[1]. This magnetometer is not absolute but measures changes in field from the field in which it is cooled below its critical temperature.

Another superconducting magnetometer utilizes the zero resistance property alone. This device consists of a superconductive ground plane which is vibrated rapidly (100 kHz) near a pickup coil[2]. A working magnetometer has not been completed, but field resolutions of the order of 10^{-10} gauss have been projected with this circuit.

The most promising superconducting magnetometers utilize various manifestations of the ac and dc Josephson effects[3,4,5,6]. Brian Josephson predicted in 1962 that supercurrents could tunnel through a thin dielectric barrier without developing a voltage drop[7,8]. Further, he predicted that a critical current exists above which a voltage would be developed. For finite voltages, the supercurrent in the junction oscillates at a frequency directly proportional to the voltage, as given by the Josephson equation

$$h\nu = 2eV,$$

where

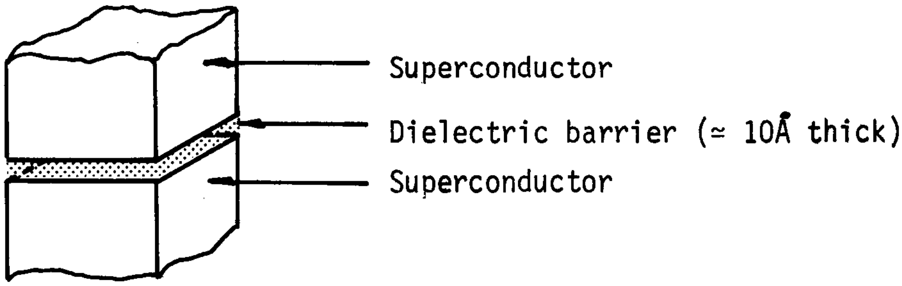
h = Plancks constant
ν = frequency
e = electron charge
V = Voltage.

The basic property of the Josephson type magnetometer is that a region connecting two superconductors can be constructed such that magnetic flux can alter the quantum mechanical phase of the superconducting electrons. This region may be a dielectric barrier, a point contact, a drastically reduced cross-section area, or a small region where the superconductivity is weakened by the proximity of another metal. Junctions of these various types are shown in Figure 1.

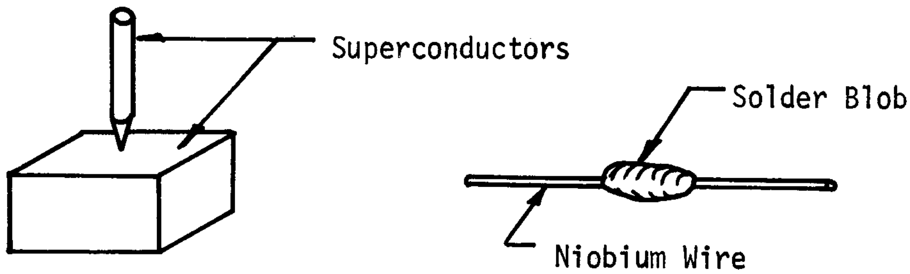
Of the numerous possible junctions, it is generally felt that the dielectric barrier and point contact types are less reliable and more difficult to manufacture in a predictable fashion. The reduced area (or weak link) and proximity type junctions are easily constructed using standard microcircuit techniques and with a reasonable development effort, Josephson junction detectors could be as readily available as transistors.

We will now consider a specific superconducting magnetometer that uses a weak link sensor and radio frequency drive and sense electronics. The basic circuit is shown in Figure 2.

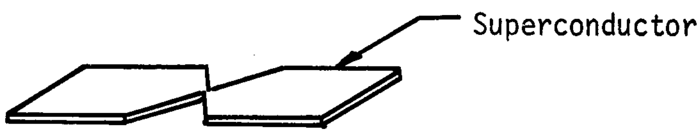
Most of the weak link magnetometers use a cylindrical sensor with the weak link formed along one side of the cylinder by mechanical scribing or photo-resist masking and then, chemical or sputter etching. The cylinder is typically the order of 0.1 cm in diameter by less than 0.5 cm long. Most sensors have been constructed from tin or lead with some recent work using niobium and niobium nitride. The superconducting film is vacuum deposited on a dielectric cylinder, usually quartz, and is from 200 to 1000 Å thick. The weak link is about 1μ long (length measured in the direction of the film axis), as shown in Figure 2.



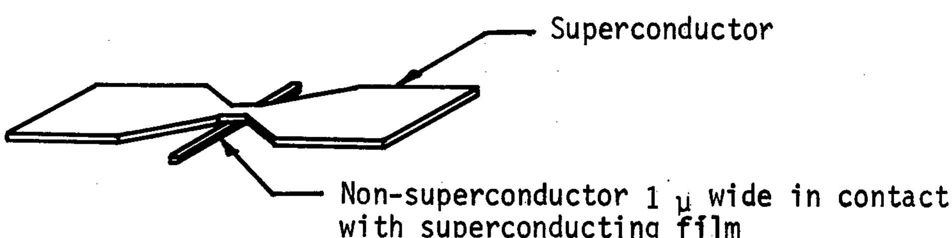
(A) Thin Film Junction



(B) Point Contacts (ref. 4 and 10)



(C) Thin Film Bridge (weak link)(ref. 5,6)



(D) Proximity Effect (ref. 6)

Figure 1: Josephson Type Junctions

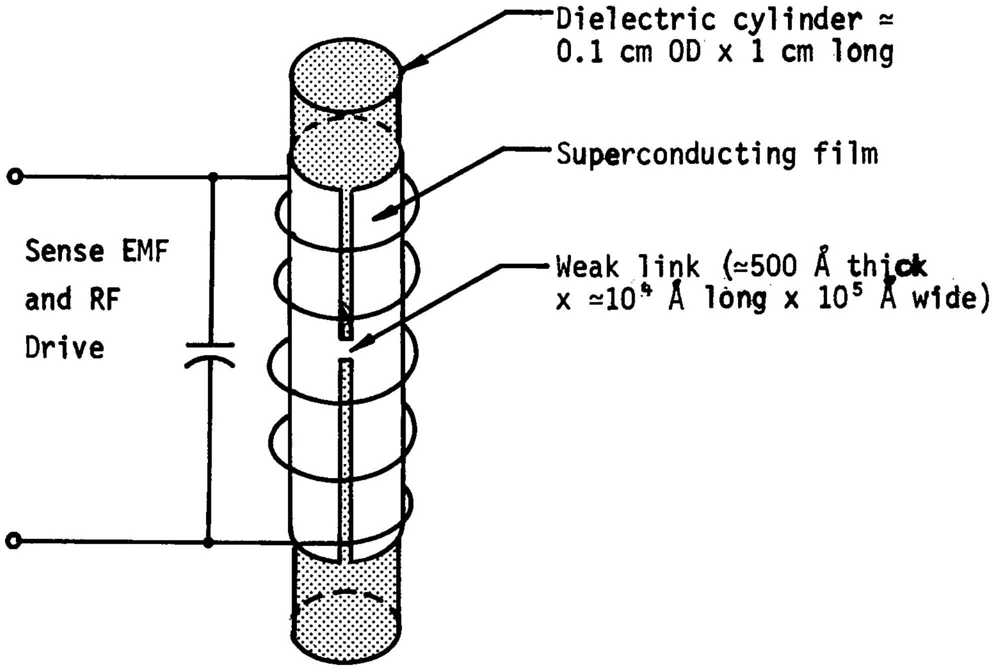


Figure 2: Superconducting Magnetometer Sensor

It has been shown by Mercereau[5,9] and others that the signal voltage developed by an rf field driven weak link magnetometer will have the form

$$\text{emf} = \omega\phi_{rf}\, J_1\left(2\pi\frac{\phi_{rf}}{\phi_o}\right) \cos\left(2\pi\frac{\phi_{dc}}{\phi_o}\right) \sin \omega t$$

where ϕ_{rf} = amplitude of the rf drive field

ω = rf drive frequency

ϕ_{dc} = ambient magnetic flux

J_1 = 1st order Bessel function.

The signal voltage from point contact and weak link magnetometers has been found to fit this relationship at least qualitatively.

A simple model of the operation of this type of element as a magnetometer is based on the use of the weak link as a magnetic flux switch[5,11]. This model provides a proper understanding of how magnetic field changes are detected and gives sufficient detail so that circuit parameters, such as operating frequency, sensor temperature, weak link dimensions and sensor size, may be determined with reasonable accuracy. Significant properties such as kinetic inductance of the superelectrons, exact waveform, L/R times for the ring-weak link during switching, etc., have been omitted for simplicity. References 4, 5, 11, 12 cover these points in detail.

UNCLASSIFIED

First, consider a superconducting ring whose thickness is several penetration depths (i.e., thickness 1000 Å or more). If the ring is superconducting and a magnetic field is applied parallel to the axis of the ring, then a circulating current will be induced in the ring. The magnitude and direction of this current exactly cancels the applied flux change. This current continues to flow as long as the field change is maintained. Thus, the ring exhibits perfect diamagnetism where the induced current is a linear function of the applied field. If the external field is increased far enough, the ring will revert to the normal state since the critical field and/or critical current will be reached. At this critical point, the shielding property of the ring is lost and magnetic flux enters both the superconducting material and the hole of the ring.

The weak link device is essentially the same structure except one section of the ring is reduced in cross-section area. The circulating current must all flow through this weak link, thus the current density in the weak link will be much higher than in the remaining ring. The critical current of the weak link is determined by the material, size and operating temperature. If an external field change sufficient to produce several units of magnetic flux ($\phi_o = 2 \times 10^{-7} \text{g cm}^2$) linking the ring will induce a current exceeding the critical current, then the circulating current-field plot will take the form shown in Figure 3.

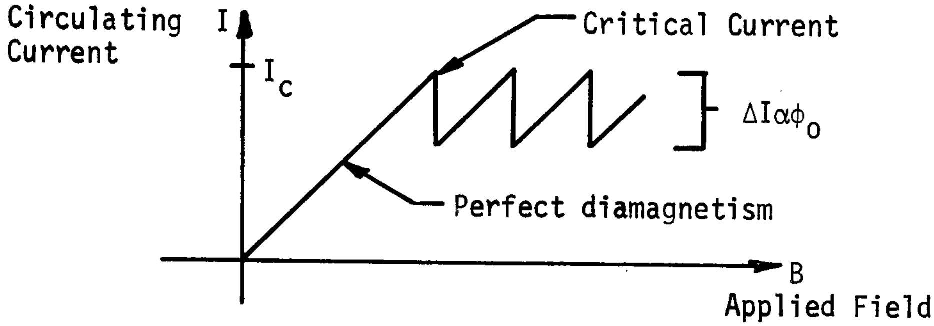


Figure 3: Current-field for a Superconducting Ring with a Weak Link

When the circulating current reaches its critical value at the weak link, the link allows magnetic flux to enter the ring. This flux change reduces the current below its critical value and the link becomes superconducting again. The amount of flux that enters the ring when the link is non-superconducting is not precisely defined, but it must be integral numbers of flux quanta and, for low currents, each jump will usually correspond to one flux quanta, ϕ_o. Now, we will consider the case where the critical current of the weak link is equal to to the circulating current induced by an applied flux change of 0.75 ϕ_o. The circulating current-field plot for this case is shown in Figure 4.

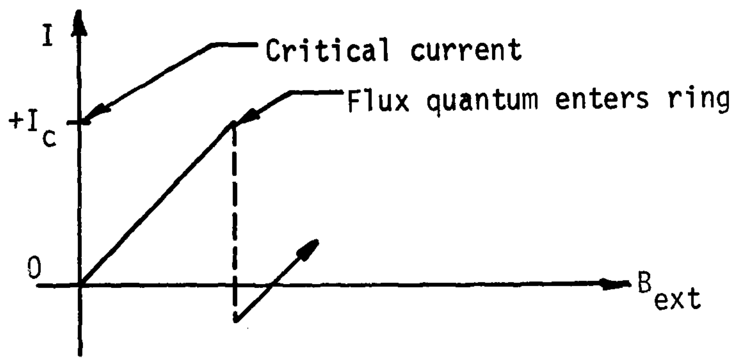


Figure 4: **Current Field for Superconducting Cylinder with Weak Link where** $I_c \alpha\ 0.75\ \phi_o$

Notice in Figure 4 that the circulating current actually changes direction at the transition when one flux unit enters the ring. This is because the total magnetic flux linking the ring must be quantized and the current will flow in such a direction to fulfill this quantization condition and maintain the lowest energy state for the ring.

If the applied field starts at zero, increases to B_1, then is reduced back to zero and then to $-B_1$, the circulating current-field plot becomes as shown in Figure 5.

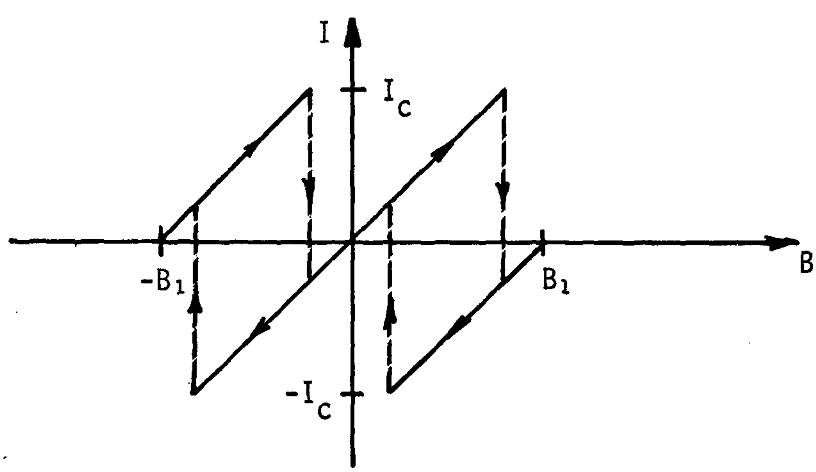


Figure 5: Current-field for the Critical Current Proportional to $0.75\phi_o$

This dependence of circulating current versus applied field is fundamental to the magnetometer operation. If B_{app} is a sinusoidal field given by $B_{app} = B_0 \sin \omega t$, then the reaction of the ring with a weak link will be as shown in Figure 6.

Figure 6A shows the circulating current versus applied field for zero ambient field and for an applied field proportional to $0.2\phi_0$ (dashed lines - Figure 6A). The sinusoidal drive field is shown in Figure 6C immediately below 6A. The switching points, marked 1 through 4, are projected directly down from 6A. These points show when flux quanta enter or leave the sensor as the circulating current reaches the critical current. Figures 6B and 6D show the voltage pulses and circulating current changes, respectively, that correspond to this flux switching. The amplitude of each voltage pulse is equal and directly proportional to the flux quanta, ϕ_0. The exact shape of the pulse depends on the inductance of the sensor and the resistance of the weak link while it is in the flux flow (dissipative) state.

The response of the sensor to a change in the ambient magnetic field is also shown in Figure 6. This response can be traced through figures 6A, B and C by following the flux switching points. A change in the ambient field proportional to $0.2\ \phi_0$, as shown in Figure 6, induces a circulating current in the sensor that essentially biases the current-field plot, as shown in Figure 6A. The resulting voltage pulses (signal) remain at constant amplitude but change relative position.

Most detection schemes now being used sense the fundamental component of the Fourier waveform generated by these voltage pulses. Both the amplitude and phase of this fundamental waveform change with changes in the ambient field. Detection of either or both of these changes then constitutes a measure of the ambient field change. In general, the response is a periodic function of the applied field where the period is proportional to the flux quantum, ϕ_0. A servo feedback circuit is used to provide a linear output versus applied field.

The general electronics used with weak-link type superconducting magnetometers are shown in Figure 7.

MAGNETIC FIELD AMPLIFIERS

The magnetic field resolution of any magnetometer may be increased with a field amplifier or flux concentrator. The use of ferromagnetic pole pieces is well-known as a technique for concentrating field. The flux density at the pole tip is magnified from the free space value in proportion to the permeability and geometry of the ferromagnetic material.

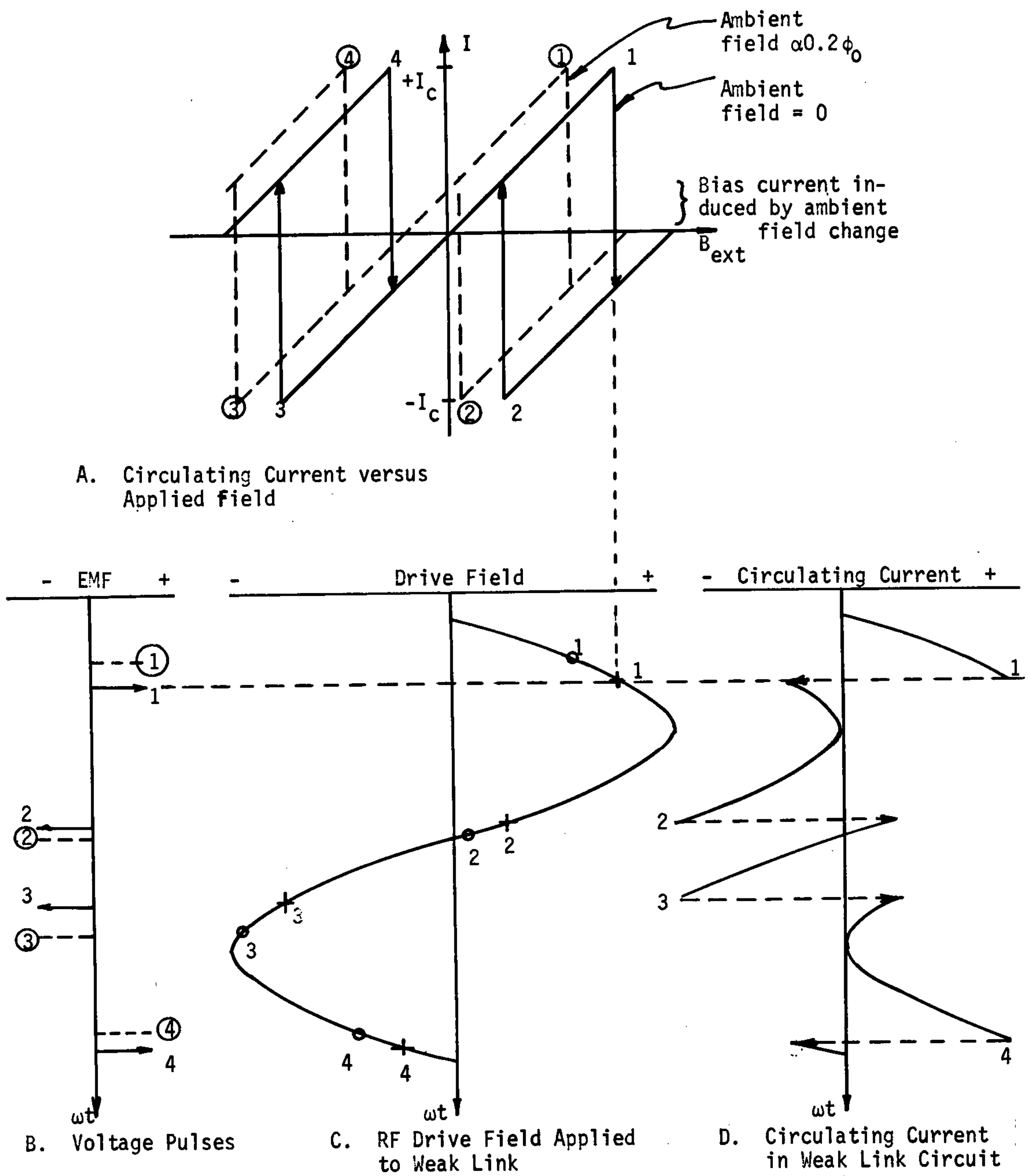


Figure 6: Response of Weak-Link Magnetometer to Ambient Magnetic Field Changes

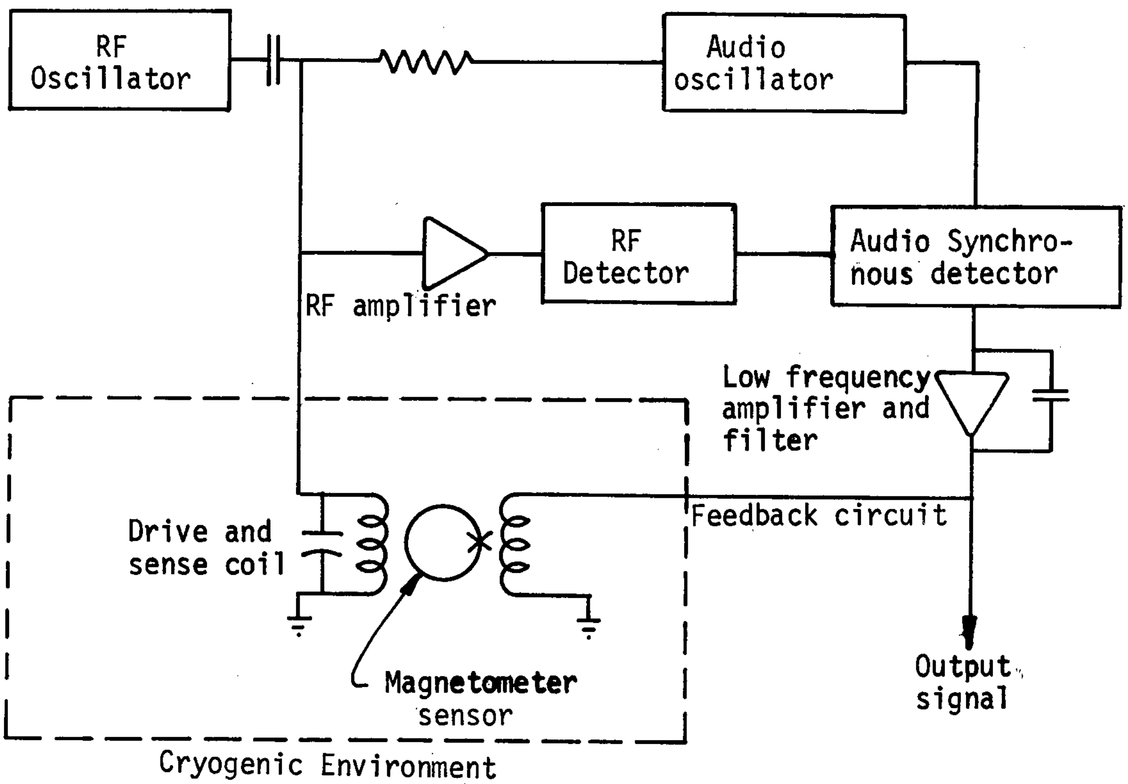


Figure 7: Weak Link Magnetometer Circuits

Superconductive circuits provide a technique for noiseless field amplification by factors of up to several hundred. This amplifier is essentially a transformer that operates down to zero frequency. A field amplifier circuit coupled to a magnetometer is shown in Figure 8.

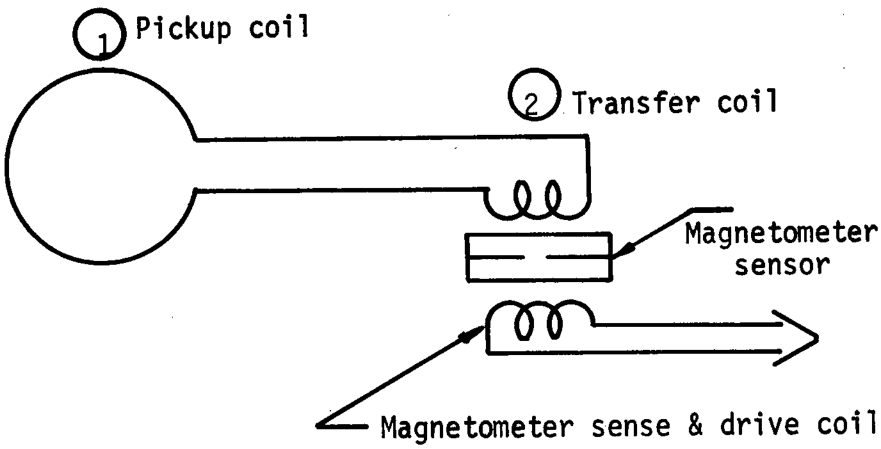


Figure 8: Superconducting Magnetic Field Amplifier

The complete amplifier circuit is made of superconductive material. Once this circuit is cooled below its critical temperature, the total magnetic flux linkages contained within the circuit must remain constant. This is because of the zero resistance property of superconductivity. Thus, if the ambient field is changed at the pickup coil, the internal field at the pickup coil will change and so will the field at the transfer coil - these changes satisfying the condition that the total flux linkages must remain constant.

The resulting field amplification can be determined from the circuit parameters as follows: Coil 1 is a large field pickup coil and coil 2 is a field transfer coil coupled tightly to the magnetometer. If the magnetic flux linking coil 1 is changed by an amount $N_1\delta\phi_1$, where N_1 is the number of turns of coil 1 and $\delta\phi_1$ is the applied flux change, then a circulating current will be induced in the coils, as given by

$$I = \frac{N_1\delta\phi_1}{L_1 + L_2}$$

where L_i and L_2 are the geometric inductances of coil 1 and 2 respectively.

The resulting field at the sensor (field transfer coil) is a function of the induced current I and the geometry of the transfer coil, i.e., dimensions, turns. The field amplification will then be this field at the sensor, B_2, divided by the applied field, B_1.

Maximum transfer of energy from the applied field at the pickup coil to the sensor occurs when the inductance of the two coils are equal, $L_1 = L_2$. This can be shown by equating the final energy $E = \frac{1}{2} LI^2$ of the two coils and realizing that the maximum energy that can be transferred is one half the applied energy. We can also derive the equal inductance relation by equating the current in coil 2 to the current induced by the flux change $\delta\phi_1$ at coil 1:

or

$$I_2 = I_1$$

$$\frac{N_2 \phi_2}{L_2} = \frac{N_1 \delta \phi_1}{L_1 + L_2}.$$

Solving for the flux in coil 2:

$$\phi_2 = \frac{N_1}{N_2} \delta\phi_1 \frac{L_2}{L_1 + L_2}.$$

In general, the inductance of a coil is a function of the square of the number of turns, thus we can write

$$L_2 = N_2^2 L$$

where L is a function of the remaining geometrical parameters. Thus,

$$\phi_2 = \frac{N_1}{N_2} \delta\phi_1 \frac{N_2^2 L}{(L_1 + N_2^2 L)}$$

For maximum flux in coil 2, set $\frac{\delta\phi_2}{\delta N_2} = 0$ to get $L_1 = L_2$.

For special cases where the coils are long solenoids such that $B = \mu_0 NI/\ell$, we can write

$$B_2 = \frac{\mu_0 N_2 I}{\ell_2}$$

but

$$I = \frac{N_1 \delta\phi_1}{L_1 + L_2}$$

$$\therefore \quad B_2 = \mu_0 \frac{N_1 N_2 \delta\phi_1}{\ell_2 (L_1 + L_2}$$

We showed that $L_1 = L_2$ and the applied field is $B_{app} = \delta\phi_1/A_1$, thus the field amplification for this case is

$$\frac{B_2}{B_{app}} = \frac{1}{2}\,\frac{N_2}{N_1}\,\frac{\ell_1}{\ell_2} = \frac{1}{2}\,\frac{N_1}{N_2}\,\frac{A_1}{A_2} = \frac{1}{2}\sqrt{\frac{V_1}{V_2}}$$

where V_1 and V_2 are the volumes of the solenoids, $A_1\ell_1$ and $A_2\ell_2$, respectively. If the coils are not long solenoids, we must use the appropriate field and inductance expressions for the particular coil to derive the field amplification. In general, the field transfer coil should be small while the pickup coil should be as large as possible. A circuit has been tested where the pickup coil was one turn of 0.005 cm niobium wire wound on a 1 cm diameter form[1]. The field transfer coil was about 180 turns of 0.005 cm Nb wire. The measured field amplification was a factor of 50.

PROTON PRECESSION MAGNETOMETER

If a system of protons, such as water, benzene, kerosene, etc., is placed in a magnetic field, the protons become polarized and the magnetic moments will precess about the field direction at a frequency given by simple relation

$$\omega = \gamma B$$

where ω is the precession frequency in radians per second, γ is the gyromagnetic ratio and B is the applied field. A field of 10^{-3} gauss corresponds to a precession frequency of 4 Hz. An excellent general review of the use of magnetic resonance methods to measure weak magnetic fields has been given by Grivet and Malnar[13].

A measure of this precession frequency is a direct absolute measure of the magnetic field in terms of the atomic constant γ. At fields above a few hundred gauss, the protons become sufficiently polarized that the magnetometer can be continuous reading, that is, we need only put the magnetometer sample in a pickup coil and measure the frequency of the voltage induced by the precessing magnetic moments. At lower fields of the order of 1 gauss, the signal amplitude from the precessing moments is very small since the magnetization as well as the frequency is a linear function of the field, so special techniques have been developed to obtain adequate signal-to-noise, even at low fields.

First, the protons are magnetized (polarized by a strong field 200-800 gauss). This field is then removed abruptly (in from 2 μsec to 50 μsec) and the magnetic moments of the protons quickly begin to precess about the unknown ambient field with frequency given by

$$\omega = \gamma B_{ambient}$$

The signal is the voltage induced by the large moments precessing at a low frequency. The signal amplitude decays exponentially with a time constant characteristic of the sample - usually 1 to 10 seconds. Figure 9 shows a typical schematic of the operation of a proton magnetometer.

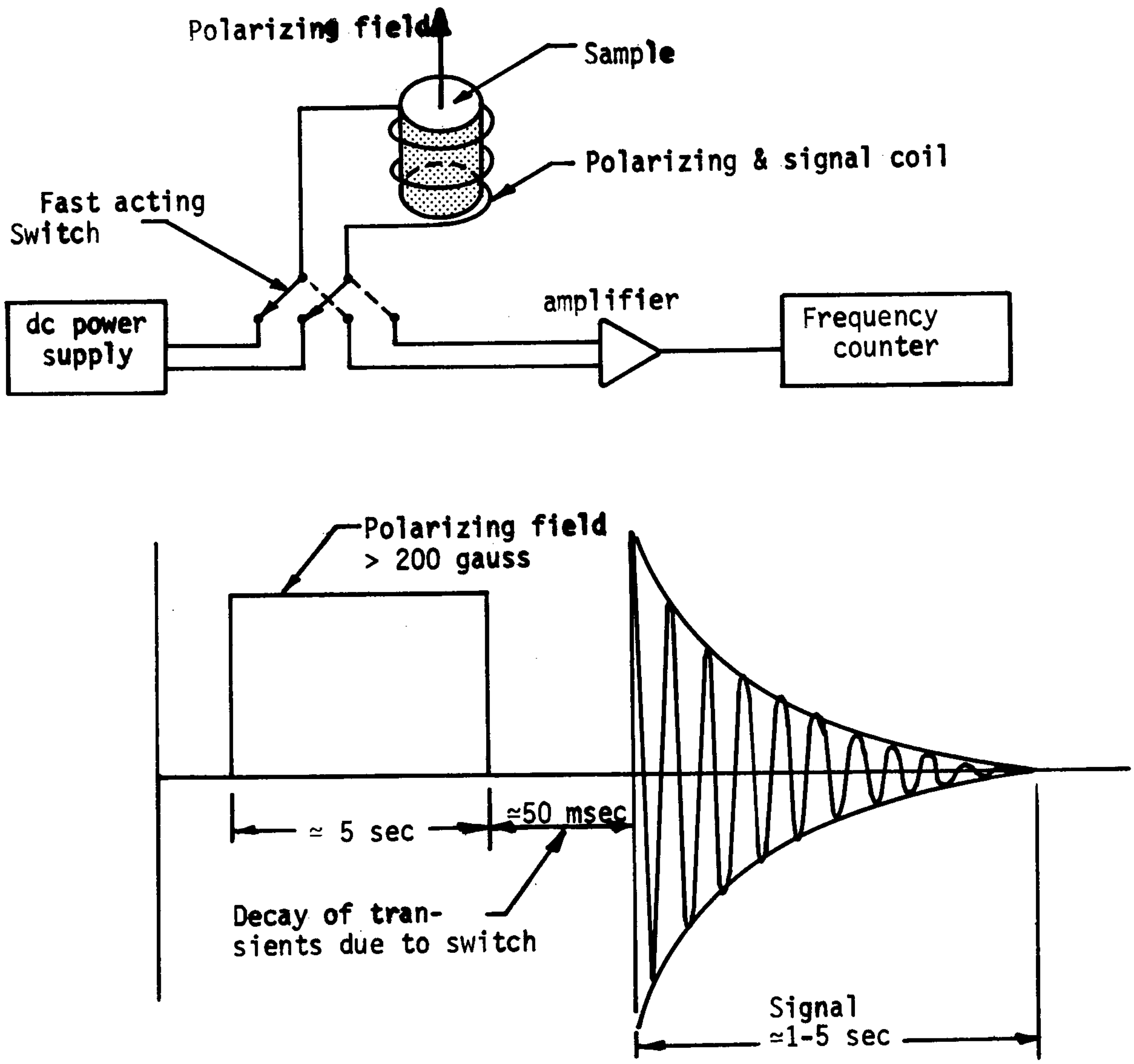


Figure 9: Basic Proton Magnetometer Operation

The sample container is usually toroidal with a common polarizing and sense coil wound directly on the toroid.

The proton magnetometer is a total field, absolute reading magnetometer and field sensitivities as good as 5×10^{-7} gauss with one reading per second have been obtained.

OPTICALLY PUMPED MAGNETOMETERS

Optically pumped magnetometers consist of a cell of helium or alkali metal vapor that is excited by light from a source of the same vapor[13] There are two general types of these magnetometers: 1) A resonance type that measures scalar field changes and 2) a non-resonance type that measures vector field changes. Both types use essentially the same optical pumping apparatus. In its simplest form, an optically pumped sensor consists of the components shown in Figure 10.

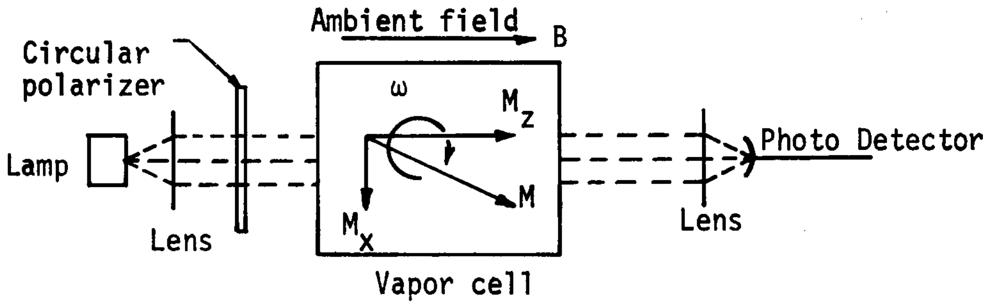


Figure 10: Basic Optically Pumped Magnetometer Sensor

The light source uses the same material as the cell, i.e., helium gas or alkali metal vapor. The light is circularly polarized and shines on the cell. The vapor in the cell is excited by this light from its atomic ground state energy level to various optical levels. Each of these levels (ground state and optical) may be split into closer magnetic (Zeeman) levels by the presence of a magnetic field.

Optical pumping occurs because the transition probabilities out of the ground state magnetic sublevels are not equal for each level because the pumping light is circularly polarized, while the decay from the excited levels back to the ground state is almost entirely due to spontaneous emission and decay occurs equally to all ground state sublevels.

Since the ground state sublevels are populated equally by decay but are depopulated by the absorption of pumping light at unequal rates, then unequal population of these sublevels will result. This resulting state is called the optically pumped state and it is more transparent to the pumping light than is the unpumped gas. It is the measure or modulation of this transparency that is used to determine the ambient magnetic field.

The Resonance Magnetometer

The optically pumped state can be removed by applying a magnetic field to the cell at right angles to the pumping light and at the frequency corresponding to the energy difference between the ground state magnetic sublevels. This RF field essentially equalizes the excitation probabilities for the ground state sublevels. At low magnetic fields the ground state sublevels are separated by equal energy and thus, by equal frequency. The sublevel resonant frequency is directly proportional to the ambient magnetic field as given by

$$\omega = \gamma_{\ell} B \qquad \gamma_{\ell} = \frac{g_F \gamma_e}{2}$$

g_F = Landé factor

γ_e = gyromagnetic ratio for free electron

Two different circuits have been used for monitoring the magnetic resonance frequency of optically pumped magnetometers and, hence, for measuring the magnetic field. One is the controlled oscillator[13,14] and the other is the self-oscillating circuit[13,15] - either of the circuits can be used with alkali-vapor or helium magnetometers. The magnetic field resolution is not affected by the circuit used, but the frequency response and location of "dead zones" is dependent on the detection scheme as will be described below.

Optical pumping orients the magnetic moments of the pumped gas in the direction of the ambient magnetic field. The transmission of light through an optically pumped gas is <u>directly</u> proportional to the magnetic moment in the direction of the light. As shown in Figure 10, the magnetic moment precesses about the field direction. This moment vector will have a component Mz along the magnetic field and a component Mx perpendicular to the field. Transmission along the light beam is a maximum when Mz is a maximum, i.e., when the gas is fully pumped.

The controlled oscillator uses the component, Mz, parallel to the field to determine the field; while the self-oscillating circuit senses the component, Mx, perpendicular to the field. Figure 11 shows a schematic of a controlled oscillator circuit.

The RF oscillator is set at a frequency near the precession frequency ($\omega = \gamma_{\ell} B_{ext}$ for the external field. This frequency is swept at a much slower rate, Ω, back and forth through the resonance frequency. When the RF field is at resonance, the magnetic moment, Mz, is decreased thereby decreasing the optical transmission of the gas cell. This mod-

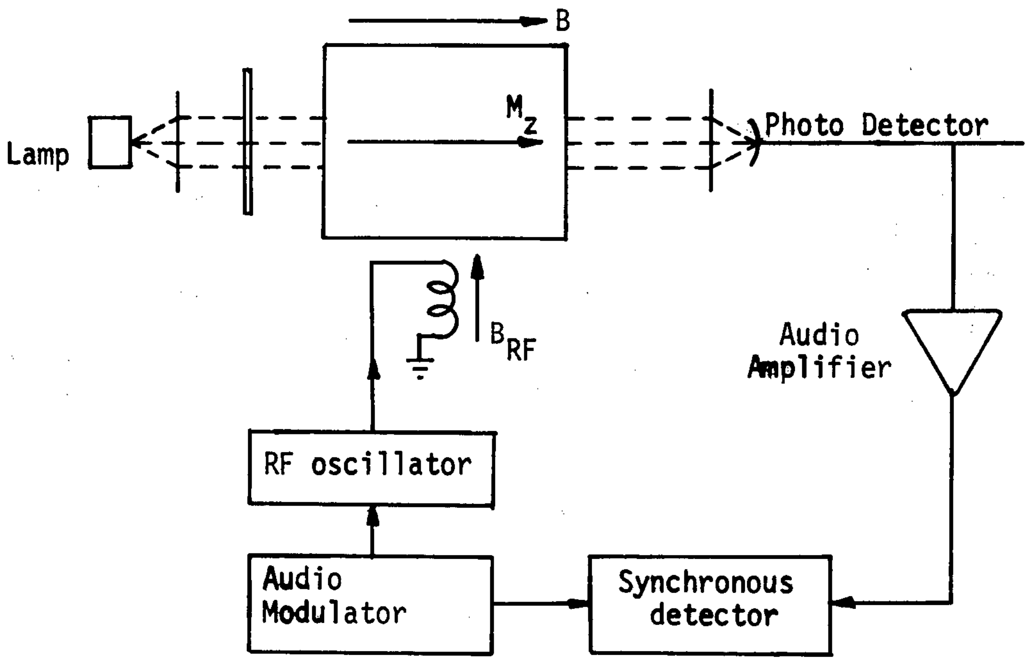


Figure 11: Controlled Oscillator Circuit

lation of the optical transmission will occur at frequency Ω, typically in the low audio range. The phase of the detected signal relative to a reference signal from the modulator is then used to determine the precession frequency and hence the external magnetic field.

This detection scheme has maximum signal-to-noise when the magnetic field is directed along the pumping light. The signal amplitude decreases approximately as $\cos^2\Theta$ where Θ is the angle between the field and the pumping light. Thus, the detection scheme has zero signal for magnetic fields perpendicular to the pumping light axis. Its frequency response is limited by the audio sweep frequency.

The self-oscillating technique uses the variation of the magnetic moment perpendicular to the pumping light to obtain a measure of the precession frequency. Figure 12 is an idealized schematic diagram of this circuit.

The circuit shown in Figure 12 uses one light source for optically pumping the gas cell. A second much weaker source is used to observe the optical transmission in the direction normal to the pumping light. This transmission is modulated at the precession frequency which is proportional to the ambient field, as discussed earlier in this section. The modulated signal is detected with the photo detector, amplified and fed back to the radio frequency coil with the proper phase to produce

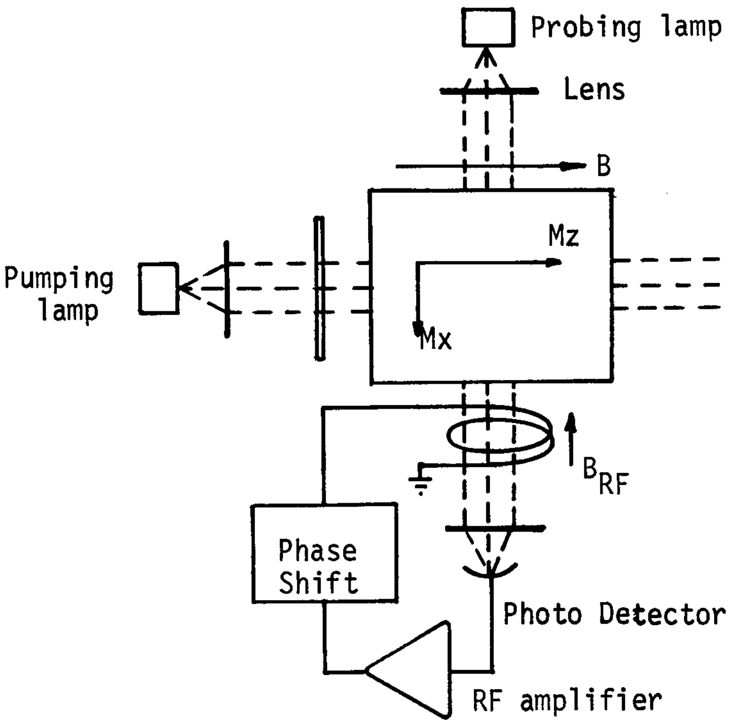


Figure 12: Self-Oscillating Circuit

self-oscillation. The RF field is applied perpendicular to the external field, B.

The self-resonant frequency of the oscillator driven by the probing light is then the Zeeman frequency which varies from the 100 kHz range to several MHz for earths field measurements. For the circuit shown in Figure 12, the signal is again approximately proportional to $\cos^2\Theta$ and the signal is zero when the field is perpendicular to the pumping light.

Most, if not all, self-oscillating magnetometer circuits use a single light source for pumping and probing. This simplifies the optics but introduces an additional dead zone. Figure 13 shows this circuit schematic.

The RF field coil is usually aligned along the light beam because of mechanical simplicity. The active component of the RF is in the direction perpendicular to the external field. In this arrangement, the pumping light is the component of the light directed along the magnetic field and the probing light is the component normal to the field. Thus a dead zone (zero signal) occurs when the field is parallel to the light beam (the same as having zero probing light in the circuit shown in Figure 12) and another when the field is perpendicular to the light

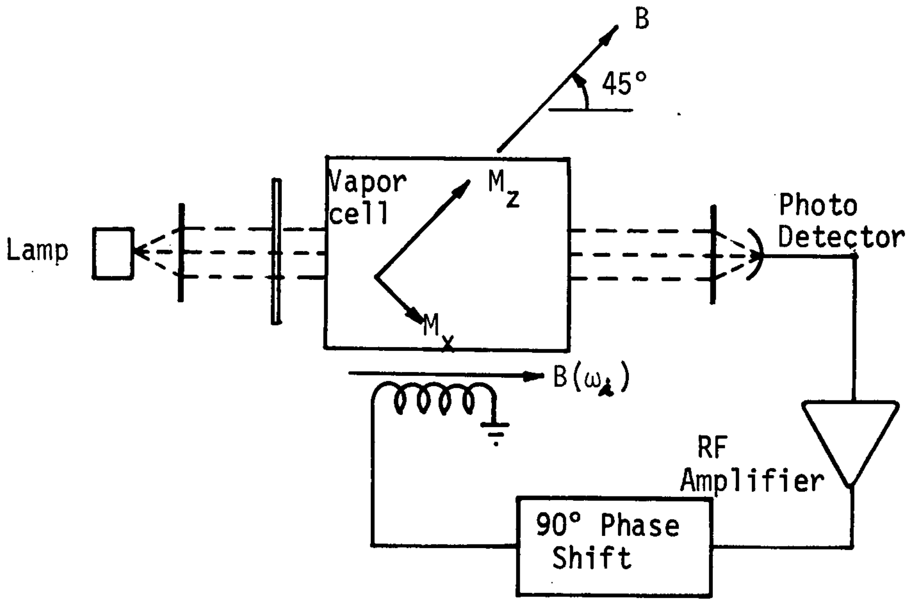


Figure 13: Self-Oscillating Circuit with a Single Lamp

beam (no pumping light).

Many variations of the above detection scheme have been developed. Magnetometers using a single light source with two cells mounted back to back are used where field sensitivity is desired with the external field in either hemisphere. The dead zones can be almost completely eliminated for any field direction by using 6 gas cells spaced about a single light source.

The Vector Optically Pumped Magnetometers

As we have seen, the resonance optically pumped magnetometer provides scalar field information by measuring the frequency corresponding to the spacing between the ground state Zeeman levels.

The non-resonance magnetometer makes use of the fact that the optically pumped state can be "switched" on and off by magnetic fields perpendicular to the pumping light axis[14]. When the magnetic field is perpendicular to the light axis and exceeds the line width (10^{-6} gauss for rubidium, 10^{-3} gauss for helium), then the ground state levels have equal absorption probabilities and optical pumping is modulated. Thus, optical pumping can be modulated by controlling the magnetic field at the absorption cell. The general operation of the magnetometer can be explained by referring to Figure 14.

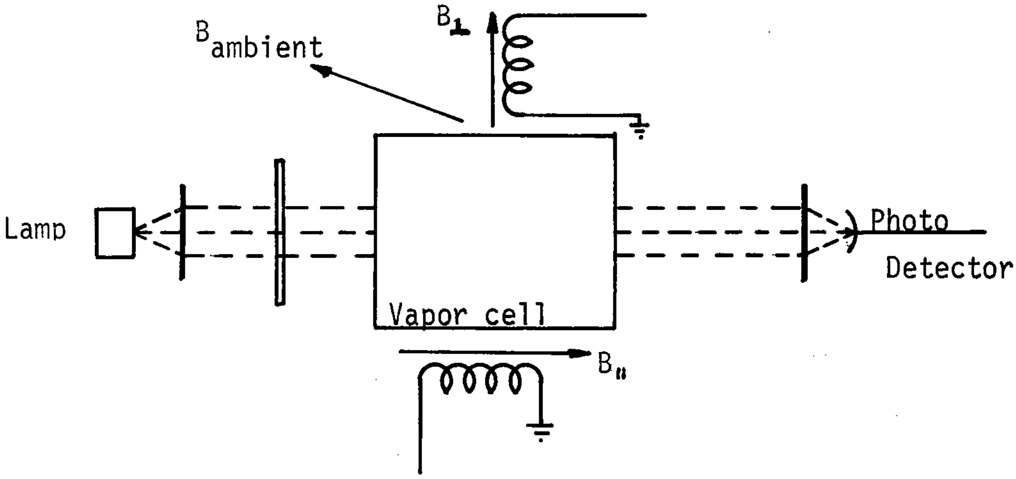


Figure 14: Vector Optically-Pumped Magnetometer

Assume that the cell is in a zero magnetic field environment. The light excites the gas in the absorption cell to the optically pumped state where its transparency is a maximum. If a magnetic field is applied along the light beam direction, the pumped state remains, although the spacing between the magnetic sublevels will change proportionally to the field. If, on the other hand, the field is applied perpendicular to the light beam and the field parallel to the beam is near zero, then the pumped state is removed when this perpendicular field is increased to the line width of the gas in the absorption cell.

If the field parallel to the light beam is not less than the line width, then optical pumping can occur even with fields applied perpendicular to the beam, but this pumping is still modulated by the transverse field. A signal is obtained by applying a time dependent field normal to the beam (or a rotating field in a plane containing the beam) and detecting the modulation of the pumped state with a photo detector. The phase of the detected signal, with respect to the drive field, is then proportional to the ambient magnetic field. The magnetometer is used with a feedback circuit to cancel the ambient field change from zero where the final signal is the feedback current directly calibrated in magnetic field in the direction of the axis of the feedback coil.

Two non-resonance magnetometers have been reported. The first one was a 3 axis sensor used on the Mariner IV and V satellite experiments[16]. This was a helium sensor and had a minimum field resolution of about 1 μG. The sensor was designed to operate in magnetic fields up to about 2 milligauss. Later versions of this sensor now in use at the Jet Propulsion Laboratory have field resolutions of about 0.5 milligauss in ambient fields up to 1.5 gauss[17]. This sensor uses a rotating magnetic field to modulate the optical transmission. This field does not have to reduce the total field through zero.

The second optically pumped vector magnetometer has been developed by a group in France[18,19]. This magnetometer uses the zero field resonance effect (Hanle effect) with a rubidium sensor. For this magnetometer, the ambient magnetic field at the sensor is maintained less than the line width (about 1 microgauss for Rb^{87}).

COMPARISON OF MAGNETOMETER PERFORMANCE

The previous sections of this paper have presented a simplified description of the operation of three different types of sensitive magnetometers. It is difficult to rank these magnetometers in any absolute fashion since we have considered differential vector sensors, absolute total field sensors and absolute vector sensors, each with very different sensitivity, size and operating characteristics. A summary of typical performance specifications will be given, followed by a general discussion of these specifications.

The following section summarizes the performance and other characteristics of the sensors discussed above. Also included in the section are suggestions of future research and development that the author feels would be of benefit in optimizing sensor performance for Navy applications.

PERFORMANCE SPECIFICATIONS

Superconducting Magnetometer

Vector field sensor - measures changes in field after sensor is operating. Best sensitivity $\approx 10^{-9}$ gauss rms in 1 Hz bandwidth.

Very small - 1 to 2 mm OD x 5 mm long, not including cryostat.

Requires liquid helium temperatures for operation. Cryostat could be as small as a 2 liter flask for several days continuous operation.

Unique potential as a vector gradiometer. (See papers by J. Nicol and J. Wynn, this conference proceedings.)

Rapid frequency response in commercially available instruments. 1.5 kHz at about 5×10^{-8} gauss rms resolution. Potentially MHz response at 10^{-9} gauss.

Will operate in fields from above the earth's field down to absolute zero with no degradation in performance.

Future Development:

Probably most significant development for the next few years will be to exploit the existing sensitivity in useful devices.

Small, highly efficient cryostats for passive liquid helium cooling.

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Closed cycle refrigerators that will operate with sensitive magnetometers.

Even smaller microcircuits operating at higher, probably microwave, frequencies.

The instrinsic sensitivity limit has not been reached and is not clearly understood. Future development could increase the sensitivity by several orders of magnitude.

Proton Precession Magnetometer

Scalar sensor - measures absolute total field. Best sensitivity $\approx 5 \times 10^{-7}$ gauss with 1 second sample times.
Relatively large - $\approx$8 inches OD sphere.
Operates at room temperature with minimal temperature control.
Can measure total field gradient using two sensors.
Very low frequency response <1 Hz for sensitive measurements.
Simplest sensor and electronics of all magnetometers being considered.

Future Development:

Sensor is well developed and understood.

Major future improvements will be in data processing and packaging.

Cesium (or Rubidium) Vapor - Resonance Magnetometer

Best sensitivity - 5×10^{-8} gauss peak-to-peak in a 2 Hz bandwidth.
Scalar sensor - multiple cells, up to 6, are used to eliminate dead zones.
Relatively large sensor - 8 inches OD sphere for 6 cell device.
Operates near room temperature. Light source and cell require temperatures from 35°C to 65°C. Multiple cell devices tend to compensate for temperature changes.
Rapid response possible at reduced sensitivity (100 kHz response is feasible). Commercially available magnetometers in the U.S.A. are self-oscillating type. F.M. detectors in the systems limit response to 20 Hz.
Complex but well developed electronics.
Optical components - lens alignment, polarizers, filters.
Dead zones exist for single cell (zero signal for field direction along the pumping light direction) cone centered about light beam direction (polar zone) and equitorial zone - normal to light beam. Maximum signal for field 45° to light beam (for single light source self-oscillating magnetometers).
Operates in fields from above earth's field down to about 5×10^{-5} gauss. At lower fields, a stable bias is required.

Future Research:

Present instrument is well developed.

May expect some performance increase from improved testing and selection of magnetometer components to minimize magnetic contaminates near the sensor and thereby reduce the heading error. New photo detectors may improve signal-to-noise by 10 to 20%. Careful selection and balancing of components in multi-cell devices will reduce heading error and temperature sensitivity.

Helium Resonance Magnetometers

Best sensitivity 5×10^{-8} gauss rms in a 2 Hz bandwidth.
Scalar sensor - multiple cells, up to 6, are used to eliminate dead zones.
Relatively large sensor - ≃ 8 inch OD sphere for 6 cell device.
Operates at room temperature. Temperature control of sensors is not required for ambient temperatures between -55°C and +55°C.
Rapid response is possible at reduced sensitivity (100 kHz response is feasible). Commercial instruments in U.S.A. use controlled oscillator circuit and are thereby limited to about 10 Hz response.
Optical requirements - lens alignment, polarizers, filters.
Dead zone in equitorial zone only (for single cell). Maximum signal when field is parallel to light beam direction (for controlled oscillator circuit).
Operates in fields from above earth's field down to 10^{-3} gauss. At lower fields, a stable bias is required.

Future Research:

Present instrument is well developed.

May expect some performance increase from improved testing and selection of magnetometer components to minimize magnetic contaminates near the sensor. This can reduce the heading error, also, new photo detectors may improve signal-to-noise.

Rubidium Vapor Non-Resonance Magnetometer

Best sensitivity - $\approx 10^{-9}$ gauss for 3 second time constant.
Vector sensor - developed by researchers in France (ref. 18, 19).
Sensor size - ≃ 2 inches OD x 6 inches long.
Operates at room temperature. Same basic requirements on temperature, electronics, optics, etc., as resonance rubidium sensor.
Ambient field must be below the line width (10^{-6} gauss for Rb^{87}) for sensor operation.

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Future Research:

Basic studies in low and stable magnetic field enclosures to determine optimum performance.

Helium Non-Resonance Magnetometer

Best sensitivity 10^{-7}gauss.
Vector sensor
Sensor size - 6 inch OD sphere for 3 axis sensors.
Operates at room temperature. Same basic requirements on temperature, electronics, optics, etc., as resonance helium sensor.
Will operate in ambient fields up to 1.5 gauss.

Future Research:

Basic studies in low and stable magnetic field enclosures to determine optimum performance. Increased sensitivity by several orders of magnitude are expected.

GENERAL DISCUSSION

We will compare these different magnetometers on the following five characteristics: Sensitivity, field dependence (vector or scalar), size, response frequency, operational difficulty.

1. The superconducting magnetometer is clearly the most sensitive magnetometer and one may expect several orders of magnitude improvement in the future. This sensitivity is essentially independent of the absolute magnitude of the ambient field from above the earth's field to zero. The resonance optically pumped magnetometers require an ambient background of at least one line width ($\approx 0.1\gamma$ for alkali vapor to 100γ for helium). The non-resonant types require that the ambient field be less than this line width. The field constraints may complicate operation.

2. Vector and scalar magnetometers have many significant applications for magnetic surveying. Relatively large magnetic anomalies, such as ore deposits, may be localized easily with scalar measurements and, in these cases, the scalar sensor has clear advantages, especially its freedom from signals induced by the sensor motion in the earth's field.

If small magnetic anomalies are being searched for, the use of vector magnetometers as well as vector gradient sensors provide unique information. As will be discussed later in this conference by J. Nicol and J. Wynn, the simultaneous measurement of the vector magnetic field and independent field derivations will determine the magnitude, orientation and distance of a distant dipole moment. The potential of vector field and field derivative magnetic surveys is just beginning to receive attention for Navy problems.

Of course, using ultra-sensitive vector magnetometers and gradiometers in the field will present many problems. Sensitivities of at least 10^{-8} gauss are needed to provide sufficient field information. Using vector magnetometers of this sensitivity on moving platforms, such as airplanes, is very difficult. Further, noise in the vector field is several orders of magnitude larger than this sensitivity of 10^{-8} gauss, so superior signal processing will be necessary.

A vector gradiometer presents more difficult problems concerning the magnetometer platform. Since the gradient is more sensitive to nearby magnetic objects, noise from the airplane, etc., may seriously limit the usable sensitivity.

The non-resonance optically pumped magnetometer may compete with present superconducting magnetometers in ultimate field resolution. The relatively large size of the optically pumped sensor requires large baselines for gradiometers using two separate sensors. Another crucial point should be made. If one uses vector magnetometers or sense coils for a gradient measurement, then the sensor axis must be precisely aligned and rigidly fixed relative to each other or noise due to relative motion of the sensors will predominate. The use of superconducting sense coils vacuum deposited on a rigid substrate, such as quartz, and operated at temperatures near absolute zero results in a much more rigid structure than can be obtained at room temperature.

The superconducting sensor is much smaller than any of the other types of sensors except for the liquid helium cryostat or closed cycle refrigerator required for sensor operation. The size of the cryogenic environment depends almost entirely on the required run time between helium refills. A complete helium dewar with external volume of about 2 liters could be built to permit 1 to 2 days continuous operation on one fill of helium.

The response frequency of all of the sensors under discussion has not received careful study. The proton magnetometer has the slowest response, especially at high sensitivity, because long counting times must be used to obtain an accurate field reading.

The optically pumped sensors are intrinsically limited to frequencies less than the frequency difference between the ground state energy levels, i.e., the Zeeman or magnetic transitions that are used to sense the field change. This frequency lies in the range from 100 kHz to a few MHz, depending on the ambient field. For helium this frequency is 2.8 MHz/gauss and for rubidium it is 0.7 MHz/gauss. In available self-oscillating magnetometers. the response time is limited by the external electronics to frequencies less than 20 Hz, while the controlled oscillator magnetometers are limited to frequencies less than 10 Hz.

Superconducting magnetometers can be operated with drive frequencies of the order of the energy gap (≈ 800 GHz for niobium) although this has not yet been done. Successful operation has been achieved at frequencies exceeding 30 MHz. The actual frequency response is limited by the servo mechanism for a closed loop system and this is usually in the 1 to 10 kHz range.

The electronics for the superconducting and for the proton precession magnetometers are simple, reliable and easy to operate. Optically pumped sensors have the added complexity of the optical system.

The cryogenic environment of the superconducting sensor is the most unique requirement of any of the sensors being considered. The design of ultra-efficient long-hold-time liquid helium cryostats and/or the development of very light, small closed cycle refrigerators suitable for use with superconducting magnetometers will minimize the difficulties of using superconducting sensors.

SUMMARY

Magnetic field sensors with sensitivities from 5×10^{-7} to 10^{-9} gauss have been discussed. Only the least sensitive of these seem to have been used by the Navy for magnetic surveying. It appears that rapid exploitation of these tremendous increases in sensitivity, along with field derivative measurements, could materially improve the Navy's search and surveillance capability.

ACKNOWLEDGEMENTS

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QUESTION SESSION

Question: Dr. R. Hein, NRL

Have you used a superconducting shield around a sensor? Does the shield affect magnetometer performance?

Answer: W. Goree

We have used superconducting shields to provide low and stable magnetic field environments for studying superconducting magnetometers. No degradation in magnetometer performance has been experienced due to the presence of a superconducting shield. We have used shields as small as twice the sensor diameter. The shield will change the inductance of the magnetometer element and any field transfer or drive coils located inside the shield. For example, a long solenoid placed inside a long cylindrical superconducting shield will induce image currents in the shield that reduces the axial magnetic field produced by a given solenoid current. This reduction in field is proportional to the mutual inductance of the solenoid and shield and for a long solenoid will be approximately given by:

$$\frac{B_f}{B_o} = \left(1 - \frac{A\ \text{solenoid}}{A\ \text{shield}}\right)$$

where B_f = field produced by the solenoid inside the shield

B_o = field that would be produced if the shield were removed

A solenoid = cross section area of the solenoid

A shield = cross section area of the shield.

SESSION D

Thursday Morning, 5 November 1970

Chairman: CAPT W.F. Sallada, USN
Office of Naval Research

SUPERCONDUCTING THIN FILM MINI-CIRCUITS

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Introduction:

Most electronic applications of superconductivity anticipate the use of the time dependent quantum characteristics of superconductivity. And many techniques have been evolved to display these characteristics in a useful-way--ranging from Josephson tunnel junctions, Dayem bridges, point contacts etc. This lecture will outline the general physical requirements which must be met in order to achieve time dependent quantum superconductivity in any weakly superconducting device (as distinguished from a tunnel junction); characterize certain thin film circuits which have been developed based on these general principles; and discuss signal to noise ratio and sensitivity of the quantum devices.

Weak Superconductivity:

In the applications which I will discuss we will most always be concerned with superconductivity at finite voltage--and consequently a time dependent state of superconductivity which is now known as "weak superconductivity". Not too many features of this type of superconductivity have been worked out in detail but it is possible to gain some idea about the behavior of a time dependent superconductor by approximating the actual time dependence as an evolutionary sequence of equilibrium states. For this approximation to be valid the evolution must be slow enough that equilibrium can always nearly be maintained. If we are in this limit the superconductor can be characterized by a macroscopic wave function $\psi = \sqrt{\rho}\, e^{i\varphi}$, where it is presumed that a large number of electrons (density ρ) have condensed into the same quantum phase state φ, [1]. If we can neglect magnetic field effects, the electric current $j = \rho e v$ and chemical potential μ determine the time and space variation of the phase as:

$$
(1) \qquad \begin{aligned} j &= \frac{\rho e}{m} \{ \hbar \nabla \varphi \} \\ \mu &= \hbar \dot{\varphi} \quad . \end{aligned}
$$

In addition to the time and space variations described by equations (1) weak superconductivity also implies that ρ also be time dependent and thus causes some intrinsic dissipation. To describe the operation of some weakly superconducting circuits we will consider a one dimensional superconducting "wire"--that is, one so thin that the only sensible variation of the wave function occurs along the length of the wire. And for convenience we assume the wire to have "unit" cross section so that we can use current density j interchangeably with total current I. Then, writing the phase relations in terms of the experimental parameters current I and voltage V we get:

$$
(2) \qquad \begin{aligned} I &= \frac{\rho e}{m} \{ \hbar \nabla \varphi \} \\ V &= \frac{\hbar}{2e} \, (\dot{\overline{\Delta\varphi}}) \quad . \end{aligned}
$$

Note especially that the current depends on the gradient of phase $\nabla\varphi$ while the voltage determines the time rate of change of the phase difference, $\Delta\varphi$, across the length of the wire. For $V = 0$ (that is $\dot{\overline{\Delta\varphi}} = 0$), we can represent the complex wave function of this situation as in figure 1a. The radius vector in any y-z plane represents the amplitude of the wave function $\sqrt{\rho(x)}$, and we define the phase angle $\varphi(x)$ to be measured from the x-y plane, (the x direction is along the superconducting wire, length L).

<u>Stationary Current States:</u>

Figure 1a represents a current carrying state where the difference in phase across the wire is π and thus $I = \frac{\rho e}{m} \hbar \nabla\varphi = \frac{\rho e}{m} \hbar \frac{\Delta\varphi}{L} = \frac{\rho e}{m} \frac{h}{2L}$. However, the phase difference at the boundary, $\Delta\varphi$, does not uniquely specify the current carrying state. Figure 1b represents another state with $\Delta\varphi$ at the boundary equal to π but this state carries a current of

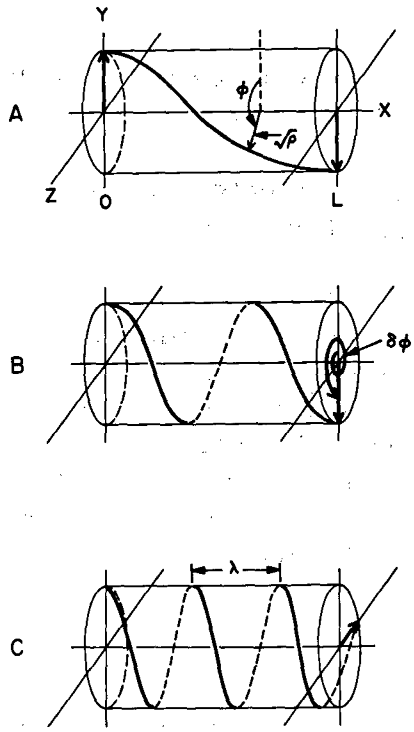

Figure 1 - Schematic representation of the wave function of a one dimensional superconductor in various current carrying states.

$I = \frac{\rho e}{m} \frac{3h}{2L}$. In general the current is determined by the gradiant of the phase or L^{-1} times the phase accumulated in going along the wire

$$(\delta\varphi = \int_{o}^{L} \nabla\varphi \, dx)$$

and not simply the phase difference $\Delta\varphi$ evaluated at the ends. Thus since there is no unique relation* connecting $\delta\varphi$ and $\Delta\varphi$, there exist many possible current carrying states, each differing in $\delta\varphi$ by 2π. In general these states also differ in current by:

$$\Delta I = \rho(\frac{e}{m}) h \, L^{-1}$$

and transitions between these various states would correspond to changes in current amounting to ΔI.

Usually the energy barrier between these states would correspond to changes in current amounting to ΔI.

Usually the energy barrier between these states is so high that transitions between states is nearly impossible and the superconductor remains at a single current level. As long as the boundary condition on phase is not changed the current will remain constant and will continue to flow without dissipation - the usual concept of superconductivity. In this case the boundary condition on phase $(\delta\varphi)$ is determined by the current I_s, supplied to the superconductor; the lowest energy state occurs when the phase difference, $\delta\varphi$ equals:

$$\delta\varphi = I_s L \left(\frac{m}{\rho e \hbar}\right).$$

*As a corollary to this mathematical statement, it follows that there is no unique relation between voltage and current in a superconducting wire. As long as the potential difference (or voltage) across the wire is zero, equations (2) tells us that the relative phase angle is stationary in time and the current continues to flow (suppose in this case there is a current source at 0 and a sink at L) without dissipation. However, if there is an independent way of changing $\delta\varphi$, independent of the current source - the current must change as we indicated before. And in particular, a change of phase difference $\delta\varphi$, by 2π corresponds to a change in current of:

$$\Delta I = \rho(\frac{e}{m})hL^{-1}$$

where L is the distance over which the current changes.

Voltage and Acceleration:

If a voltage does exist across the wire, the phase difference advances in time as

$$\dot{\Delta\varphi} = \frac{2eV}{\hbar},$$

and the wave function begins to "wind up" as represented in Fig. 1c. Figure 1c represents the wire at the instant of time τ

$$\tau = \frac{11}{4}\,\frac{h}{2eV}$$

after applying a voltage V to a non-current carrying wire. Actually Fig. 1c simply represents the result of free acceleration of the supercurrent by an electric field. As the electrons accelerate, the electron wave length λ decreases (see fig. 1c) or as I have said, the wave func- "winds up". However there is a finite critical velocity for the electrons so the acceleration cannot proceed forever. At the critical velocity an instability sets in which allows the superconductor to change its current state and is at the heart of this dynamic quantum superconducting process.

Instabilities:

As the velocity of the electrons increases so does the kinetic energy. This increase in energy of the superconducting state acts to decrease the thermodynamic favorability of the superconducting state over the normal state. And thus the number density of condensed electrons (ρ) tends to decrease with increasing electron velocity. (See fig. 2a). This decrease of density with increasing velocity produces an unusual relation for the electric supercurrent $I = \rho ev$ (see fig. 2b). In this case, the current peaks (at v_c) as a function of electron velocity and finally goes to zero at maximum velocity (v_m) where the superelectron density is zero. The velocity region between v_c and v_m is an unstable region, essentially because of an <u>inverse</u> "Faraday induction" effect. At velocities above v_c any fluctuation to increase the velocity decreases the supercurrent. This <u>decrease</u> in supercurrent will be accompanied by an induced electric field necessary to carry the "normal current", resulting from the decreased super-

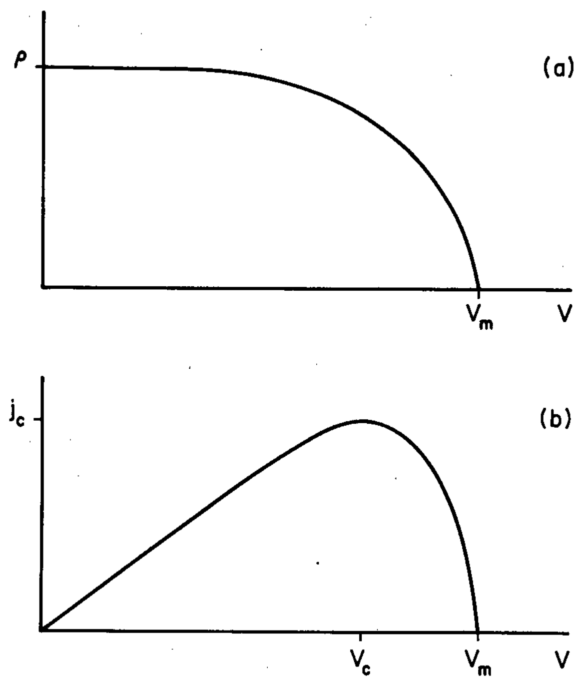

Figure 2 - Upper curve schematically represents superelectron density as a function of velocity. Lower curve represents supercurrent (ρev) resulting from the above density variation.

current, against ohmic losses. [It will turn out that the internal impedance of these devices is such that they must almost always be considered as driven from a current source.] In usual circumstances this field would act to oppose the change in current. However, in this situation although the increase in electric field does increase the electron velocity, it further decreases the supercurrent. Thus the system is unstable between v_c and v_m and will spontaneously decay.

Phase Slip Transitions:

As a working hypothesis we will combine this decay mechanism with the previous picture of the accelerating supercurrent to describe the time dependent superconducting state. Suppose the one dimensional superconducting wire of Figure 1 is attached at both ends to "large" superconductors. "Large" means that the density of superelectrons ρ in these bounding superconductors is so great that for the currents we discuss, φ can be considered constant in the bounding material [since

$$\frac{j}{\rho} = \frac{e}{m} [\hbar \nabla \varphi].$$

Since ρ must be continuous, this also implied that ρ is a function of position in the wire and $\rho(x)$ thus has a minimum value halfway from end to end of the wire, or at the "center" of the wire, (See fig. 3a).

This special variation of ρ assures that there will be only one place along the wire where instability occurs. Figure 3 is a schematic representation of the time progression of an instability occurring at the center of a superconducting wire arranged as we have described. Figures 3a-3c represent the decay of ρ in the immediate vicinity of the center of the wire due to the instability we have mentioned and 3d-3e represents the thermodynamic recovery of this region in a lower current state. Fig. 3a represents the wire initially when $\delta\varphi$ has just been brought to a value such that the electron velocity reaches v_c at the center of the wire. [Figs. 3b, c, and d represent only the central "decaying" region of the wire]. The spontaneous decay is represented as progressing from Fig. 3a thru 3c. In the time independent situation ρ usually decays over distances of about a coherence distance, ξ. Presumably in the time dependent case a similar localization will occur keeping the amplitude variation confined to about one wave length of Ψ. In fact at the critical velocity

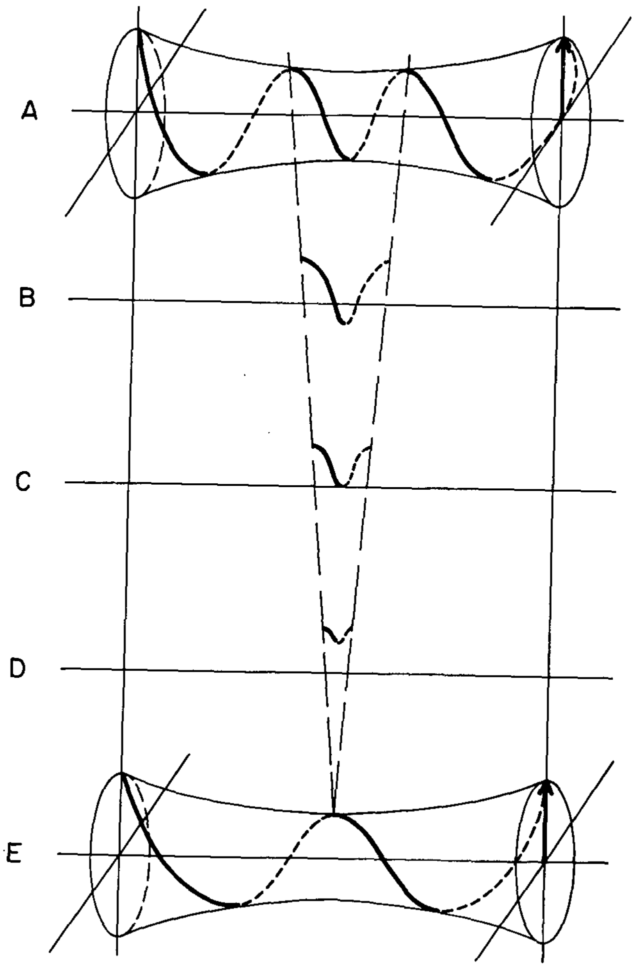

Figure 3 - Wave function for a nonhomogeneous one dimensional superconductor undergoing phase slip by 2π. Fig. b, c, and d represent various stages of the slip in the central portion of the superconducting "wire".

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it turns out that $\lambda_c \simeq \xi$. In 3b the amplitude in the immediate vicinity of the center of the wire has started to decrease and at 3c the amplitude at the center has decayed to zero. From 3c to 3e is a process of recovery. The amplitude ρ has been quenched at only one point and the surroundings are still superconducting. Thus it is thermodynamically favorable for this central region to recondense into a superconducting state. This new state must also be a phase coherent state but not the high velocity (and high energy) state from which it just decayed. Consequently recondensation occurs in the adjacent (by 2π) phase state as illustrated in Fig. 3d and 3e. The time scale for this transition process is essentially the time to reach thermodynamic equilibrium within a coherence distance or the "pairing time" $\sim \frac{h}{\Delta}$.

Thus we have described the process of phase slip in a one dimensional superconductor. The mechanism for this transition is the inherent current instability above v_c, not the Lorentz force on a moving vortex [2]. In fact it should be noted that there is no vorticity or flux quantization in this one dimensional model. During phase slip the amplitude, ρ, has been driven to zero by the instability and then has subsequently recovered thermodynamically, meaning implicitly that both the wave amplitude and phase are time dependent in this process. In the situation we described $\Delta\varphi$ was kept constant. This is not a necessary restriction, it means only that V = 0 across the wire during the transition; i.e., a "constant voltage" transition, ($\Delta\varphi$ constant and $\delta\varphi = 2\pi$). If $V \neq 0$ we can describe this situation as a superposition of phase slip and free acceleration during the time of the transition. The final current state in this situation will be the V = 0 final current state ($\delta\varphi = 2\pi$) plus an additional current due to free acceleration during the time of the phase slip. However in no case can the final current exceed the initial critical current. But in this limit such a transition might be called a "constant current" transition ($\Delta\varphi = 2\pi$ and $\delta\varphi = 2\pi$).

Both the supercurrent and kinetic energy can change during the phase slip process. For the "constant voltage" transition the current changes by $\Delta I = \rho \frac{e}{m} h L^{-1}$, as we said before. Since the coherence distance can be written in terms of the critical velocity v_c as $\xi = h(mv_c)^{-1}$ this change in current is $\Delta I = \rho e v_c(\xi/L)$, where we define $I_c = \rho e v_c$ as the critical current. The kinetic energy, $\frac{1}{2}\rho m v^2 L$, of the current carrying wire turns out to be

$\frac{1}{2}\rho \frac{\hbar^2}{m} \frac{(\Delta\varphi)^2}{L}$. And evaluating this difference in kinetic energy between two states differing in ($\delta\varphi$) by 2π leads to:

$$\Delta(kE) = \left(\frac{h}{2e}\right) \frac{1}{2} \{ I_i + I_f \},$$

where I_i is the initial current before phase slip and I_f is the final current after slip. Thus in the constant voltage transition (phase slip occurring between the critical current and some lower current level I_f separated from I_c by $\delta\varphi = 2\pi$), both current and energy change by:

$$\Delta I = I_c\, \xi / L$$

$$\Delta E = \frac{h}{2e}\, \frac{1}{2}\, \{I_c + I_f\} = \frac{h}{2e}\, I_c\, \{1 - \frac{\xi}{2L}\}\, .$$

For the "constant current" transition $\Delta I = 0$ and $\Delta E = \frac{h}{2e} I_c$. The additional energy over the constant voltage transition is required to reestablish the I_c state rather than I_f. However in both of these (and all intermediate type) transitions the amplitude ρ (and thus the current) goes to zero locally during the transition and then recovers.

<u>Repetitive Phase Slip:</u>

The model for a time dependent weakly superconducting state then essentially involves repetitive phase slip; where there is free acceleration of the supercurrent by a voltage until the current reaches the critical velocity, a spontaneous transition to a lower current state, followed by the free acceleration of the lower state to the critical velocity, at which the whole process repeats--a sort of quantum mechanical relaxation oscillation. It also implies a two fluid model of superconductivity in that at any finite voltage we assume that V/R of the current goes by "normal" processes in addition to any supercurrent that might flow. Thus any decrease in supercurrent due to phase slip is presumed to be accounted for by an increase in normal current; and an increase in potential $R\Delta I$. Therefore this model predicts a periodic variation of potential, $R\Delta I$, occurring over the interval between transitions; where the interval between transition is $\tau = \hbar / 2e\overline{V}$ and the power dissipation in the process is $\tau^{-1}\Delta E$.

In the limiting case of a wire one coherence length long these results become dimensionally independent. In the constant voltage phase slip mode the difference in current before and after the transition $\Delta I = I_c$, dissipation $P_s = \frac{1}{2}\overline{V}I_c$ and the amplitude of the oscillating potential, $\delta V \cong R\Delta I = RI_c$. In the constant current mode $\Delta I=0$, and dissipation $P_s = \overline{V}I_c$. The variation of potential in the mode occurs only during the transition itself (since $\Delta I \simeq 0$) and is thus a <u>pulse</u> of amplitude RI_c. The dissipation P_s is the power necessary to sustain the ideal superconducting phase slip process at a rate $\nu = 2e\overline{V}/h$ in the two modes we have discussed. If we supply current to the wire this model implies that a potential $\overline{V}$ must be developed as shown in Fig. 4; curve A represents the normal state I-V curve. At any voltage V, additional supercurrent can flow ranging between curve B and C. Curve B represents the additional dissipation ($\frac{1}{2} VI_c$) arising from the constant-voltage slip process and therefore also implies an additional time average supercurrent, $\frac{I_c}{2}$. Curve C represents constant current phase slip and the additional dissipation of VI_c arising from this mode.

The actual form of the oscillating potential is not at all predictable from the preceding model. The only determing factor is that the potential must be periodic with period τ given by the integral equation:

$$h = 2e \int_0^{\tau} Vdt \text{ or } \tau - h/2e\overline{V} \text{ where } \overline{V} = \frac{1}{\tau} \int_0^{\tau} Vdt.$$

However the leading term in any expansion of the actual oscillating current (or potential) must be the "Josephson" term:

$$I = I_c \sin \frac{2e}{h} \int (Vdt + \alpha) + \cdot \cdot \cdot ,$$

and thus any dynamic superconducting device of this type will resemble the Josephson junction to first order. However to optimize the device in terms of signal to noise, power, or response to an external signal (impedance matching) we must know more of the detailed dynamics and is the reason to continue the description beyond first order similarities.

Thin Film Structures:

The only real assumption so far has been, one dimensional superconductivity. However this assumption has the practical importance that it avoids the many complications of flux trapping and vortex motion associated with larger superconducting structures. Although larger structures certainly can also have a time dependent state, the "forces" causing the dynamics probably involve the Lorentz force on a vortex line and are susceptible to noise associated flux trapping and material imhomgeneities. Accordingly most electronic devices are usually designed to be in the "one-dimensional" limit. This electronically one-dimensional limit is actually not quite as severe as the mathematical one-dimensional case which requires that the cross

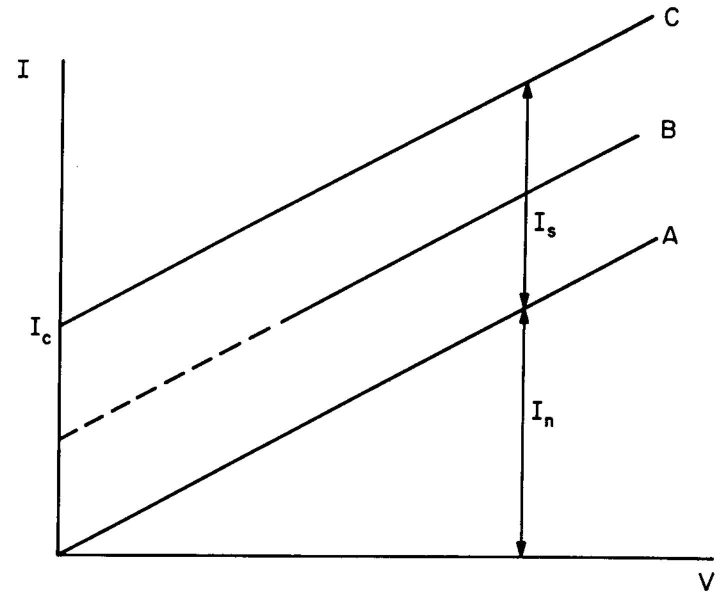

Figure 4 - Current-Voltage curves for phase slip. Curve A represents the normal state, curve B includes the additional power for constant-voltage phase slip and curve C includes the additional power for constant current phase slip. Excess supercurrent I_S may range between B and C depending on the process.

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section be less than ξ^2.

The electronic limit has two aspects; one involving the dimensions required to sustain a vortex in the material and another related to the time scale of vortex motion. The first aspect simply sets an upper bound on the diameter of a one dimensional superconductor as being smaller than a vortex. If we consider the vortex as an electrical "circuit" we can get some feeling for this limit. Since the inductance L of a loop (radius r) is roughly $L \simeq \mu r$ and flux is defined as $LI = \Phi$, then $\Phi = \mu r I_c$ is the greatest flux that can be produced by a "circuit" of radius r, with critical current I_c. For one dimensional superconductivity this must be less than $\varphi_o = h/2e$, or $\mu r I_c < \varphi_o$. Thus one dimensional superconductivity requires that the product of wire diameter and critical current roughly be less than 10^{-9} amp.; or 10^{-4} amp for a 10 micron wire.

The second limit occurs regardless of size because of damping in the dynamics of vortex motion. If we consider only eddy current damping by the normal electron background we expect that since the magnet field of the quantized flux also interacts with the normal electrons, changes in flux must be slower than R/L of the coupled normal "circuit". By "circuit" we mean some current path within the material - which has nearly the same geometry as the supercurrent distribution, (inductance L_V). Thus vortices cannot move at frequencies greater than about $\omega \sim R/L_V$. If we define I_V as the current to support a vortex in the inductance L_V then $\omega \sim RI_V/\varphi_o$ and the upper bound on ω is set by the critical current, or:

$$\omega_{max} \sim RI_c/\varphi_o.$$

Since this sets an upper frequency cutoff, at frequencies above ω_{max} no vortex dynamics are possible and the system becomes "one dimensional". Thus at voltages, $V = \omega\varphi_o$ such that $V > RI_c$ any dynamic superconducting circuit is effectively one dimensional.

Also implicit in our description is the requirement that there be only one point of decay along the wire at which the phase slips by 2π. If there are more slip points which are uncorrelated or if phase occasionally slips by more than 2π (i.e., $2n\pi$) then the simple dynamic process we have described will become "noisy" because of the randomness introduced by these new degrees of freedom. The possible randomness in the number of slip points can be minimized by making the one dimensional wire short and in the limit what we would like to achieve as the optimum configuration would be "zero dimensional" super superconductivity. That is, a configuration whose dimensions perpendicular to the current path satify $r < \varphi_o/\mu I_c$ (or operates at voltages $V > RI_c$) and whose length along the current path is only a few coherence distances. As a practical matter both of these requirements are met to a varying degree of success by the Dayem bridge and the point contact.

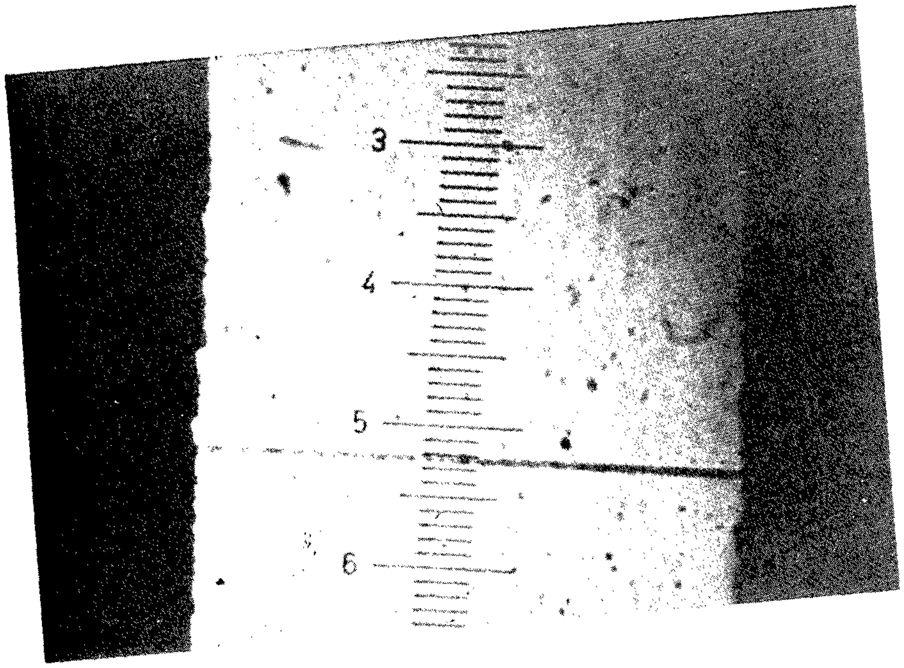
In order to examine some of the physics underlying these descriptions as well as to develop reliable superconducting devices we have been developing techniques for fabricating weakly superconducting structures of known configuration and dimension. Because of the foregoing dimensional requirements on weakly superconducting devices it was felt that films deposited on a rigid substrate offered more reliability and experimental versatility than point contacts of these dimensions. These are thin film circuits incorporating a localized material inhomogeneity to define the weakened section; and thus weaken the superconductivity without weakening the material. The inhomogeneity has been of several forms; either a "doping" of the material creating a localized alloy, a localized proximity effect or a localized annodization of the film.

The alloy or proximity effect structures used in our experiments are thin-film crossed-strips of two materials--one a superconductor and one not (Figure 6 insert). In the overlay region there is either an alloying or a proximity effect depending on the particular materials, which results in a stable superconducting material whose transition temperature (T_c') and critical current are well defined and are determined by relative thickness of the films [3]. We have used Sn-Au, Pb-Cu, and In-Cu combinations which have T_c' less than T_c of the main film. Thus the overlay section is weakened relative to the main film and forms a phase-slip region for the quantum phase. If the length ℓ of the weakened section is made the order of the coherence distance, ξ, the slip is localized and the weakened section can be thought of as a slip plane. In our experiments ℓ has ranged from less than 1μ to 40μ width w from 5μ to 10^3, and thickness from 300A to 3000A. Normal state resistance ($T_c' < T < T_c$) ranged between 10^{-4} to 10^{-1} ohm.

The annodized devices are usually of the hard superconducting films, Nb or Ta. In these films the transition temperature is a function of thickness - decreasing with decreasing thickness. For example a Nb film 500-1000A thick has nearly the bulk transition temperature ~ 8°K. Thus by locally adjusting the thickness of the film, a weakened section can be created of much the same form as in the alloyed devices. The technique in this case is to cover the metal film with photo resist, photo-etch a narrow strip across the metal film through the protecting photo resist, and then locally annodize the film through the cleared strip. In this way a localized thin section can be created with about the same dimensional range as in the alloyed devices. However in these materials (Nb and Ta) the transition temperature ranges up to about 8°K and the resistance $T_c' < T < T_c$ ranges from 10^{-2} to 10^{+2} ohms. Figure 5 shows two such circuits--A is an alloy device of Au-Sn where the length of the weakened alloy section is about 1μ and B is a Nb film device where the length annodized section is about 3μ.

A typical I-V curve, characteristic for these structures [3] is shown in Fig. 6. This curve exhibits an excess current $<I_s>$, above V/R at all voltages, becoming $I_c/2$ at high voltage, (where I_c is the maximum zero-voltage current). This behavior is typical of all structures of this type when $\ell < 2$-3μ. As ℓ increases the limiting value of the excess current at high voltage also increases. Thus the high voltage limit ($V >> RI_c$) is apparently the constant voltage phase slip we have discussed before. As V goes to zero the excess current approaches I_c and the phase slip must become a constant current process. The entire I-V curve can be modulated by a magnetic field (B) perpendicular to the film in a manner reminiscent of interference effects in the Josephson junction. Figure 6a is taken at the maximum I_c (B) near zero field; Figure 6b is taken at the same temperature but at one of the minima in I_c (B) as a function of magnetic field. We take the difference between these maximum and minimum currents to be $<I_s>$ and identify it as the time average supercurrent at any voltage V.

These phase-slip structures have also been found to produce an oscillating potential at the Josephson frequency $\nu = 2eV/h$, which has been directly measured by connecting a tuned rf amplifier and detector to the structure (see Figure 7a). The frequency of the amplifier was held constant in these measurements and the frequency of the oscillation was changed by varying the current through the device (thereby changing the dc potential). The rms amplitude of the oscillating potential $<\delta V>$ (determined by integrating the oscillation intensity



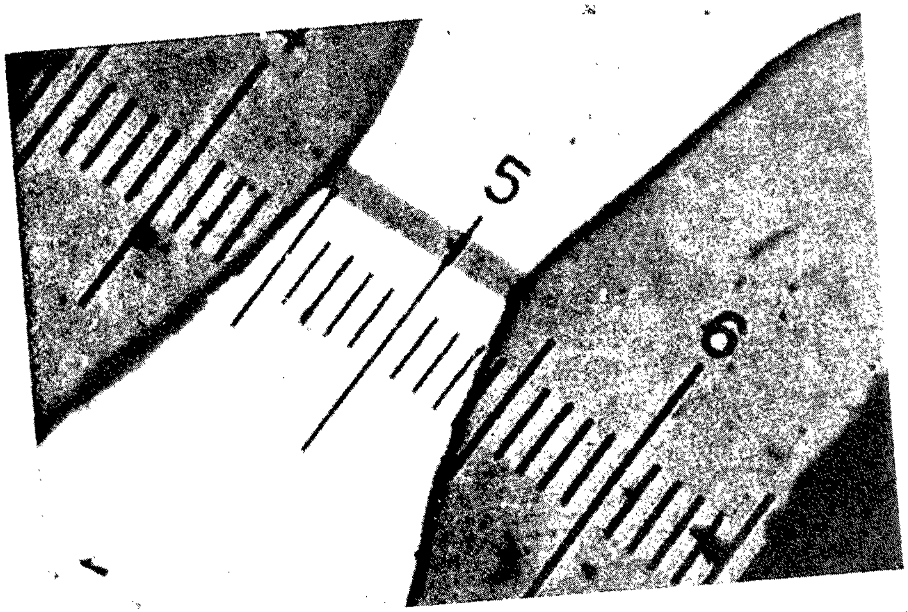


Figure 5 - Photographs of two types of phase slip devices. Upper figure, A, is an alloy device of Au-Sn, lower figure, B, is Nb.

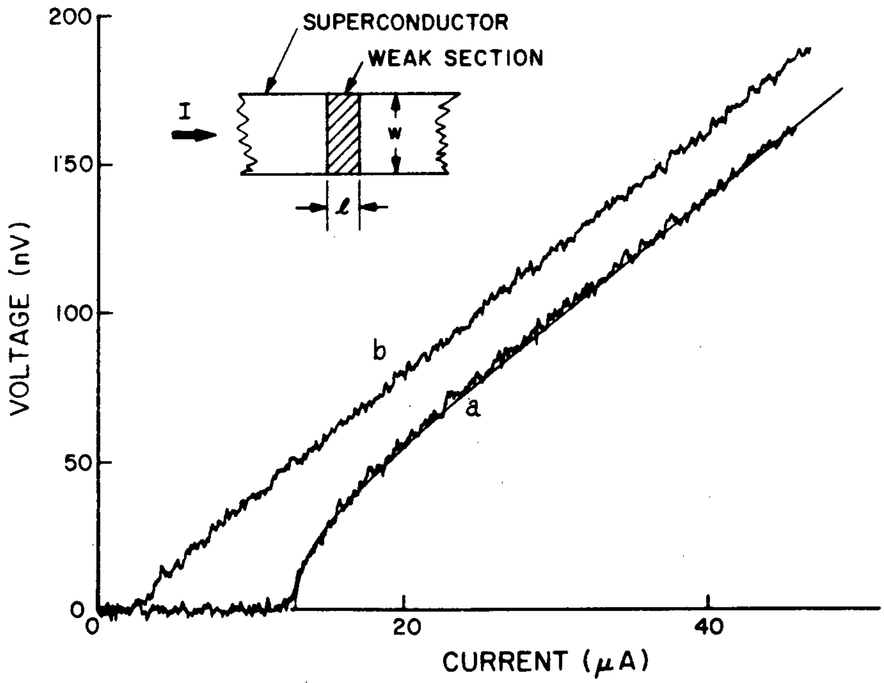


Figure 6 - Experimental I-V curves for phase slip devices showing modulation by magnetic field. Phase slip process varies from constant current at low voltage to constant voltage at higher voltage. (Note reversal of coordinates from Fig. 4). The solid line in curve, a, represents the time average of equation 3 in the text.

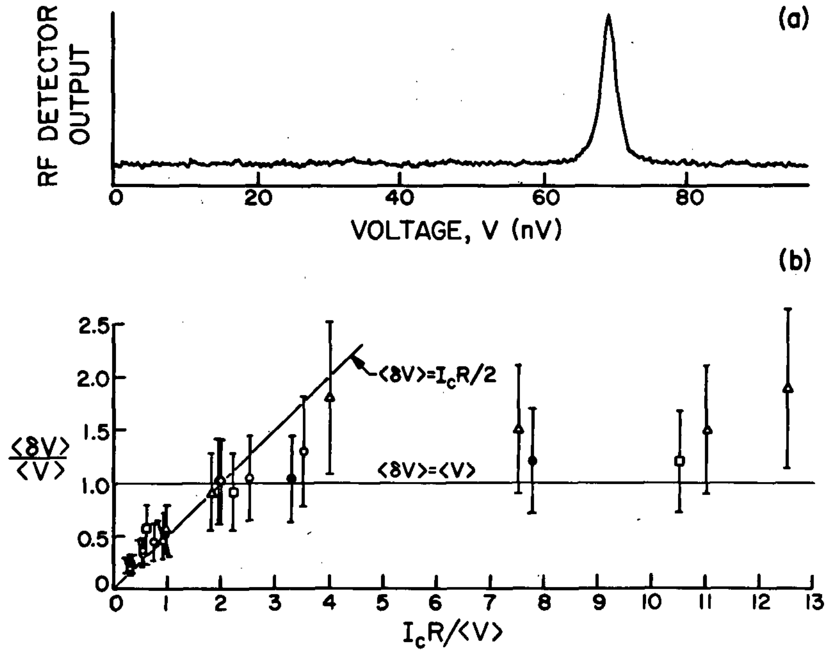


Figure 7 - Upper curve, a, shows the amplitude of the oscillating potential developed across a phase slip device. Lower curve (b) is the ratio of the oscillating potential to the dc voltage as a function of critical current, resistance and dc voltage for phase slip circuits.

over the line width), shows the amplitude dependence illustrated in Figure 7b and agrees with our previous speculation concerning the amplitude and form of the oscillating potential in the two limiting cases. From these experimental observations the following approximation for the general time dependent potential has been proposed [3]:

$$(3) \qquad V(t) = RI - \frac{RI_c}{2} \{1 + \cos \frac{2e}{h} \int_o^t V(t')dt'\},$$

when driven by a current source $I > I_c$ and R is the normal state resistance of the weak section. This form is consistent with both our experimental I-V curve, (see Figure 6b) and measurements on $<\delta V>$. For $I >> I_c$ the cos term is nearly harmonic and $<\delta V> = 1/2\ RI_c$; while when $I \simeq I_c$ there is strong frequency modulation and harmonic generation and at the Josephson frequency $<\delta V> = h\omega/2e$.

The frequency width of the tuned rf amplifier was usually considerably narrower than the oscillation line-width so the frequency spectrum (or effective current noise) of the oscillation could be obtained from data such as Figure 7a. These measured widths also correlate well with equivalent frequency width of steps induced in the I-V curve by external radiation: for radiation frequencies lower than $\Delta\nu$, the steps disappear. The current noise in these devices has been found to arise from Johnson noise in the resistance driving the supercurrent over a band width given by RI_c/φ_o [4] and thus the effective current noise is independent of resistance and equals $(\Delta I_n)^2 = \frac{kT}{\varphi_o} I_c$.

Device Sensitivity:

In summary, when driven by a current source I, these weakly superconducting devices have been found to develop an oscillating potential where:

$$\delta V = \frac{RI_c}{2} \cos \frac{2e}{\hbar} \int_o^t V(t')dt'.$$

The maximum power in this oscillating potential is $\bar{V}I_c$. This power is distributed around the central frequency $\nu = \frac{2e}{h}\bar{V}$ over a band width $(\Delta\nu)^2 = R_D^2\ (\varphi_o^{-3}\ kTI_c)$ where R_D is the dynamic resistance of the operating current. These devices have been used in magnetometer circuits [5], as radiation detectors [6], and several other applications.

As an element of a magnetometer, the effect of a flux change of one quanta in the magnetometer loop is to change the phase of the oscillating potential δV by 2π. Thus by phase detecting δV we can make a flux sensitive device whose flux sensitivity will be determined by the signal to noise in detecting the power represented by δV, (assuming no parametric effects). This will give an upper bound to the actual device sensitivity since device noise may degrade this by transferring some of the power away from the signal frequency.

For a weakly coupled amplifier with an equivalent input noise of kTB the ultimate signal to noise ratio (S/N) will be

$$(S/N)^2 = \frac{I_c V}{kTB} = \frac{I_c \varphi_o \nu}{kTB}$$

However the maximum useful current in a magnetometer circuit is determined by the inductance of the loop, or $I_{max} = \varphi_o / L$. Typical magnetometers have an inductance of $L \sim 10^{-9}$h and use room temperature amplifiers $T \sim 300°K$ so that

$$(S/N)^2 = \frac{\varphi_o^2 \nu}{LkTB} \simeq \frac{\nu}{B},$$

where ν is the operating frequency and B the band width of the amplifier. At 10^7 hz., with a one second time constant this gives $S/N \sim 3 \times 10^3$ or a flux sensitivity of $\varphi_o (S/N)^{-1} \sim 3 \times 10^{-4}$ quanta. Many of the present magnetometers are already operating at nearly this limit. Going to higher frequency $\sim 10^{10}$ hz should improve this to $\sim 10^{-5}$ quanta.

Flux sensitivity can be converted to field sensitivity by means of flux transformers and conversion factors (from gauss cm^2 to gauss) ranging from 10^{-1} to 10^{-2} have been reported. Thus it would seem that an optimistic upper bound on magnetometer sensitivity with a room temperature amplifier at the highest useful frequency would be: $(\Delta B)_{min} \sim 10^{-2} \times \varphi_o \times 10^{-5} \sim 10^{-14}$ gauss. To achieve this must also imply that the device noise must be controlled so as not to extract signal power. In first approximation that means that the ratio of the band width of the amplifier input circuit to the operating frequency.

Operation of the devices as radiation sensors often relies on synchronization of the oscillating currents by the incident radiation. Thermal fluctuations tend to destroy this synchronizing effect so that

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detection in this mode of operation is possible only when the energy of interaction with the radiation field ($\frac{1}{\omega} V_{rf} I_c$) is larger than the thermal fluctuation energy $kT(\frac{RI}{V})$. This fluctuation energy arises from a theoretical shot noise treatment [7] which predicts current noise similar but somewhat greater than that observed in these devices. Thus:

$$V_{rf} I > \frac{\omega kTRI}{V} = \frac{kTRI}{\varphi_o} \;,$$

$$V_{rf} > \frac{kTR}{\varphi_o} \;.$$

Therefore minimum detectable power,

$$P_s = \frac{V_{rf}^{\;2}}{2R} \;, \text{ is } P_{min} = R\left(\frac{kT}{\varphi_o}\right)^2 \sim R \times 10^{-15} \text{ watts.}$$

This minimum power is that required to be developed in the resistance of the device by a radiation field in order to achieve some synchronization. A corollary to this is that increasing the device resistance decreases the ultimate sensitivity of a superconducting device operating in this mode and points out the desirability of impedance matching to low resistance devices.

Prospects:

A start has been made to develop thin film superconducting devices and we have some reasonable idea of how they work and the physical limitations on their performance. The main problems remaining are the technology of predetermining the supercurrent level at a given operating temperature and the physics of the very high frequency phase slip processes. One intriguing electronic prospect is the possibility of making three or more terminal devices from these circuits by gating the weak section.

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SUPERCONDUCTING SYSTEMS FOR MAGNETIC ANOMALY DETECTION

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When the Navy talks about a MAD System it is not referring to a black box designed by a mentally deranged engineer; nor is it describing an IBM 360 out of control. It is instead referring to a system, airborne normally, for magnetic anomaly detection. The magnetic anomaly that the Navy is looking for is in fact a very very small perturbation in the earth's ambient field. These anomalies are caused by objects of interest to the Navy, and to no one's surprise these objects are submarines. The magnetic field created by a submarine, by whatever mechanism the submarine becomes magnetized, generally is of the order of 10^{-5} gauss or less. Since the earth's field is approximately 1/2 gauss, then it is clear that the magnetic anomaly for which the Navy is searching is in fact roughly 1 part in 10^5 of the total field to which a magnetic sensor may be exposed.

In the preceding papers you have heard descriptions of superconducting magnetometers with sensitivities several orders of magnitude better than those of conventional fluxgate or optically pumped atomic magnetometers. The question naturally arises whether magnetic sensors with such greatly improved sensitivities can be used for the benefit of the Navy. This provides us with an opportunity to speculate and such indeed is the purpose of this brief paper. I hope I can give you some ideas of what may ultimately be achieved by the development of new MAD Systems based upon the use of superconducting magnetic sensors--without at this time saying with confidence how these objectives will finally be achieved. For this there are two good reasons. First, if I knew all the answers I could not give them in this session; and secondly, there is still a long way to go before a decision can be made as to which design is likely to be most successful in the end. We are probably at this moment as far from the development of a practical superconducting MAD System as was today's optically pumped atomic MAD system a decade ago.

The most recent types of magnetic detectors used by the Navy for the detection of submarines from an aircraft, are optically pumped helium devices although rubidium and cesium vapor magnetometers are also available as Dr. Goree has mentioned. These systems are capable of measuring a total magnetic field with a differential sensitivity of approximately 10^{-7} gauss although this is hard to achieve regularly in practice. These devices measure the total local magnetic field; they do not indicate the direction of the source from the sensor or the size or the range of the source. In other words, existing magnetic field sensors present the captain of an aircraft who is looking for a submarine with a problem rather like that facing someone who has only his nose to help him find flowers in a dark room. He has no means of knowing their direction nor the size of the bundle of flowers he is looking for. All he can do is to start some form of search pattern in the course of which he will discover areas in the room in which the odor is stronger or weaker and thereby gradually succeed in localizing its source. So it is with present magnetic anomaly detection techniques.

If we know roughly the size of the magnetic source and assume that it can be regarded as a dipole we can calculate the range at which a sensor of given sensitivity can detect its presence. If, however, the sensor is sensitive enough to detect the external background noise which may arise from a variety of causes, then clearly the detection range of the magnetometer may be determined not by the sensitivity of the sensor, but rather by the range in which the field created by the dipole exceeds by some discernible amount the background noise field. To a very good approximation this is the case with existing airborne magnetic anomaly detectors. Only on very rare occasions is the sensitivity of the sensor inadequate for detecting the magnetic dipole at a range greater than that determined by the backgound or ambient noise. Remember also the important fact that the earth's average field is about half a gauss, or 5 x 10^6 greater than the differential sensitivity of the most sensitive total field magnetometer. The noise is caused by variations in this latter field.

Now, if the available magnetic sensors are limited by ambient magnetic noise, then we cannot expect to increase detection range significantly by improving their sensitivity. Instead we must look at the characteristics of the noise in which the magnetometer is operating to determine whether alternative detection methods would be helpful.

The background noise to which an airborne magnetic field sensor is exposed falls into four broad categories. The first, <u>geomagnetic noise</u>, is caused by natural phenomena such as lightning or electromagnetic effects in the ionosphere. These phenomena create a continuous noise background that varies in amplitude with latitude, with time of day and with season of the year. Its variability presents one of the major problems in predicting the performance of magnetic anomaly detection systems when limited by geomagnetic noise. Generally the noise originates at a considerable distance from the magnetic detector, and this leads to an important property to which I shall return later.

The second category of noise, geologic noise, arises from the fact that the magnetic sensor is moving and inevitably must pass over geological formations consisting of rocks and sediments of different magnetic properties. Consequently, the magnetic field close to these formations varies from place to place and presents to the moving magnetic sensor a magnetic field that appears to vary with time. Quite clearly, this geologic noise varies with geographical location; it also depends upon the altitude of the aircraft above the surface of the earth. At sea one would expect geologic noise to be much more important in shallow water than in deep water and such is indeed the case. Very often in shallow water, geologic noise and not geomagnetic noise determines the useful range of MAD systems.

The third type of noise, wave noise, arises from the fact that sea water is a good electrical conductor. Consequently, electrical currents are induced in ocean waves moving through the earth's magnetic field and these currents, in turn, radiate magnetic fields. These magnetic fields have spectra which are related to the spectra of the waves. The signals observed by the airborne magnetometer depend strongly upon the direction of the waves relative to the earth's local magnetic field, on the velocity and amplitude of the waves, and on the velocity and direction of the sensor relative to the waves. Fortunately, the amplitude of the wave noise diminishes rapidly with height above sea level. The problem is very complex and deserves much further research, both theoretical and experimental.

The final source of magnetic noise to which a sensor is exposed is generally described as platform noise since it arises from magnetic sources on the platform or is caused by the motion of the platform and sensor in the earth's field. For example, electric currents turned on or off on the aircraft create magnetic transients to which the sensor is sensitive. Also, as the aircraft changes direction in the earth's field, eddy currents are induced in the skin and the frame of the aircraft. These in turn radiate magnetic fields. Finally, if the orientation of the sensor relative to the earth's field is changed, and if its output is not truly independent of direction, then it will record the apparent field fluctuations as an additional form of magnetic noise.

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Any new magnetic anomaly detection system must have at least greater detection ranges than existing systems when performance is determined by ambient noise of the types I have just described. So with this in mind, let us now examine the new superconducting magnetic sensors. We observe a second attribute that we have neglected so far. In addition to their improved sensitivity, they are very small. Whereas, existing atomic magnetometers are of the order of several cubic inches in size, a magnetometer of the Josephson type is less than 1 cubic centimeter in size. Consequently, we can consider constructing arrays of magnetic sensors within a volume which is acceptable for airborne use. For example, if we consider the construction of a magnetic gradiometer, using conventional atomic sensors with sensitivities of 10^{-7} gauss, then a gradiometer sensitivity of 10^{-9} gauss/foot could be obtained by using two total field magnetometers separated by a distance of 100 feet. On the other hand, if we use two superconducting magnetometers with sensitivities of 10^{-9} gauss, the same gradiometer sensitivity can be obtained with a separation of the two sensors of only one foot. This reduction of size by two orders of magnitude permits us to consider building gradiometers with sensitivities adequate for the detection of the <u>gradients</u> of fields of magnetic anomalies and which at the same time are physically small enough to be carried on an aircraft.

Having reached this situation we can now go one step further and consider a possible configuration. If we were to construct a gradiometer using conventional total field magnetometers, we would measure the field gradient by finding the difference between the magnetic fields observed by two sensors separated by, in the above example, 100 feet. We would, therefore, have to face the difficult problem of extracting a very small difference between two large signals since each sensor would be exposed to the earth's total magnetic field, which you will recall is approximately 1/2 gauss. So we are talking about measuring a difference in the magnetometer outputs of 1 part in 10^7. If, however, we make use of the properties of superconductors, we can adopt an entirely different approach. We can measure the actual field difference between two points by using only one superconducting magnetic field sensor and by replacing the two sensors at the two points of observation by superconducting coils connected in series opposition in a totally superconducting circuit.

Let me make this clear by referring to Figure 1. As shown schematically, the magnetic gradiometer consists of two coils located 1 foot apart, with diameters of approximately 2 inches. These <u>field</u> coils are equal in area and are connected in series opposition. The circuit includes a third small coil which we shall call the <u>sensor</u> coil; the entire circuit is <u>superconducting</u>. The sensor coil is enclosed within a magnetic shield, also probably superconducting, while the two field coils are exposed to the local magnetic field which is a combination of the earth's field (approximately half a gauss) and the field of the magnetic anomaly for which we are searching. If the fields to which the two field coils are exposed are the same, then there is no net flux through the system and, consequently, no current flows around the superconducting circuit. If,

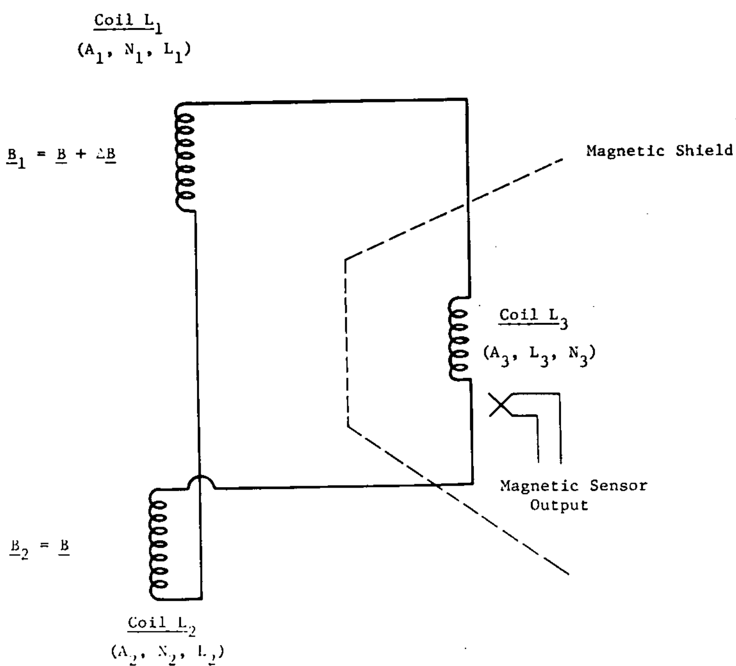

Figure 1: Schematic Arrangement of Gradiometer Field and Sensor Coils

however, the assembly is exposed to a non-uniform field, then the field, and consequently the magnetic flux, through one field coil is greater than through the other. By the principle of flux conservation in a superconducting circuit, this net flux creates a circulating current through the superconducting circuit including the sensor coil. There it creates a local field that is proportional to the difference between the magnetic fields at the two field coils. The field caused by the net current through the circuit at the sensor coil is observed by the superconducting magnetometer. As a result, the small sensitive superconducting magnetic sensor does not have to measure the large ambient field with a sensitivity of approximately 1 part in 10^9; instead it measures only the field difference which is of the order of 10^{-9} gauss.

The system, you will notice, differs in two important respects from the gradiometer which could be constructed in principle from conventional magnetometers. Not only is it smaller physically by two orders of magnitude, it also measures field differences directly.

By adjusting the relative sizes of the field coils and the sensor coil, it is possible to magnify the effective field difference seen by the field coils, as mentioned yesterday by Dr. Goree. When the desirable areas of field and sensor coils are taken into consideration, it is not unreasonable to expect a field magnification of about 10. So that with a magnetic sensor with a sensitivity of 10^{-9} gauss it should be possible to observe a gradient of 10^{-10} gauss/foot--let us call that "today's target". Further, from much of the evidence available today, it appears that the presently available superconducting sensors may be limited by electronic circuit noise. If this is true, then it is reasonable to hope for an improvement in instrument sensitivity by a factor of ten, say to 10^{-10} gauss, and of gradiometer sensitivity to 10^{-11} gauss/foot--let us call that "tomorrow's target".

Suppose we now examine in quantitative terms what these gradiometer sensitivities imply. First we consider the case in which an existing total field magnetometer is limited by geomagnetic noise of various amplitudes. The comparison is made in Table I, from which I have omitted actual detection ranges and instead normalized all ranges to that of the "typical" detection range of the best modern total field magnetometer. The detection ranges of the gradiometer are based on the assumption that geomagnetic noise, because its origin is remote, is uniform over the volume of the system, i.e., the noise gradient is zero.

TABLE I

MAD DETECTION RANGES

Geomagnetic Noise	Total Field Magnetometer	Gradiometer Sensitivity 10^{-10} gauss/ft	Gradiometer Sensitivity 10^{-11} gauss/ft
Unusually quiet	1.95		
Typical (good)	1.0	1.85	3.3
Poor	.4		

It is important to emphasize not only the improvement in detection range in the best of circumstances but, above all, the increased usefulness of the system because of its ability to see through magnetic noise, and increase poor detection ranges by a factor of perhaps more than eight.

There are, however, other benefits which may be obtained by further development of the gradiometer approach.

You will recall that the magnetic field of a dipole is inversely proportional to R^3, so that the first and second spatial derivatives are inversely proportional to R^4 and R^5 respectively. Consequently the ratio of $\frac{dH}{dr}$ to $\frac{d^2H}{dr^2}$ is proportional to R, so that if these two quantities can be measured at the same time, then it is possible to calculate simultaneously the range to the magnetic dipole. Further, the physical size and sensitivities of the magnetic sensors that we have talked about are such that it appears possible to construct, in one assembly, two first derivative magnetic gradiometers, the difference between which will provide the second spatial derivative of the magnetic field. Again we are faced by the fact that the amplitude of the second derivative signal is lower by the factor R, than that of the first derivative gradiometer. Nevertheless, it appears that at useable ranges, it should be possible to determine the actual range to the anomaly.

There is an alternative approach: Of the nine first derivatives of the magnetic field (dH_x/dy etc.), only five are independent. If we make the assumption that the submarine is in a horizontal position, then, in principle, these five measurable quantities can be used to solve explicitly for the five unknown quantities required to define the submarine's magnetic moment, direction and position relative to the sensor--at least as far as the submarine can be described as a dipole. By either approach, we introduce an entirely new aspect into the search for underwater magnetic sources.

One of the major problems in submarine detection is the geologic noise, which, particularly in shallow water, can mask the magnetic signal of the target. There are two principal differences between the target of interest and competing magnetic sources: 1) the unwanted magnetic sources are generally much larger, and 2) they usually appear deeper than the target of interest. Because of the latter, it may now be possible to distinguish a submarine in shallow water where previously a MAD System could not operate because of geomagnetic and geologic noise.

All of this is not obtained without additional technical complexity. It will be necessary, for example, to greatly reduce the platform noise created by the aircraft. This will require a reduction in the magnetic signals radiated by the aircraft and improved sensors to sense the motion of the aircraft, particularly its changes in magnetic heading. These signals will be fed into the computer forming part of the magnetic detection system to reduce the platform noise. The problem of wave noise is still under study and a great deal of work remains to be done but it appears that a gradiometer assembly may be able also to assist in the detection of the submarine in wave noise limited circumstances.

In considering the ultimate realization of a new MAD System, we have adopted the point of view that a system of this complexity cannot be developed to its full working potential for several years. Within that time, there will undoubtedly be improvements in many associated technical areas. For example, the development of improved sensors to sense the motion of the aircraft, is one area; another is the development of small complex dedicated computer systems. If it is possible to develop a computer that is as complex and as small as that required to land a spacecraft on the moon, then surely we can develop a small unit to perform the numerical calculations that are involved in extracting and processing the spatial derivatives of the magnetic field to be measured and used in detecting magnetic anomalies.

Similarly, we do not consider cryogenic refrigeration a major problem area. Already there exist compact airborne cryogenic systems operating at temperatures below 15°K. Larger systems for use on the ground operate reliably at 4°K and lower. It is completely reasonable to expect the development of compact airborne systems operating at 4°K within the next few years provided there is justification. But it is not at all clear that the operating temperature of the system need be as low as 4°K. Work is underway to develop superconducting sensors that will operate at considerably higher temperatures. Any rise in the operating temperature would, of course, greatly simplify the development of the entire system (recall J. G. Daunt's discussion), although even at 4°K, the refrigeration equipment presents no major weight or power penalties.

An experimental laboratory program is now underway with two objectives. First, to find and hopefully solve the problems involved in building a first and second derivative magnetic gradiometer system based upon the principles that I have outlined; second, to confirm the validity of the assumption of the uniformity of geomagnetic noise over small volumes and to establish that, indeed, a small superconducting magnetic gradiometer will operate with the required sensitivity in the presence of geomagnetic noise that would dominate a total field magnetometer of high sensitivity. The program has been underway for only a brief period. Recently we have received the magnetic sensor with a sensitivity of almost 10^{-9} gauss and are now going through the steps of consummating a successful marriage with the superconducting gradiometer circuitry. We expect to be able to say within a few weeks that we have successfully demonstrated the combination of the two and completed a superconducting magnetic gradiometer with a sensitivity better than 1 x 10^{-9} gauss/foot. Figure 2 shows the apparatus now in use in the laboratory and the construction of the gradiometer assembly.

In conclusion, lest I be accused of uncritical optimism, I want to make it clear that several difficult problems remain to be solved before a new airborne magnetic anomaly detection system, using superconducting magnetic sensors can become a reality. Let me mention just two of the principal areas:

(1) The basic assumption that is made in support of a gradiometer configuration is that the gradients of geomagnetic noise, over small volumes, are negligible. Plausible arguments can be made in support of this assumption but there is virtually no experimental evidence to justify it. Clearly measurements of the gradients of geomagnetic noise with adequate sensitivity are essential.

(2) Mechanical distortion of the gradiometer, whether caused by thermal effects or twisting, bending or flexing, introduces undesirable signals, particularly if the unwanted signal derives from the earth's total field. These effects depend critically upon the geometry and construction of the selected configuration and will play an important role in determining the final system. It does not appear that thermal or mechanical distortions need limit the sensitivity of the system. But it is clear that particular care must be given to the selection of the system including the details of the mechanical design to ensure that maximum sensitivity is obtained.

For the above reasons, I would like to repeat my opinion that any selection of a system design or configuration on the basis of present knowledge may be premature. For most problems that have arisen so far we believe we can see at least reasonable solutions--although they have not been tested experimentally--but we cannot be sure that we have foreseen all problems. All we can say is that the program will require research in many areas of geomagnetism and basic and applied physics, together with important developments in electrical and mechanical engineering before a new MAD System, based upon superconducting sensors, can deliver the important improvements in performance of which it appears to be capable.

Figure 2:

Laboratory Assembly Showing Experimental Gradiometer System

Mr. Michel, NSRDL Annapolis: Which organization is supporting the contract that you are working on?

Dr. Nicol: ONR, Code 461.

Dr. Hein, NRL: Must you shield this thing when you cool it down? You have a big superconducting loop. How do you avoid frozen-in flux when you cool it down?

Dr. Nicol: I think we have a trick for designing around that problem so that we shall not have to use a shield. We'll know whether the trick is going to work or not after we try it. We haven't done it yet.

Question by anonymous person: You talked about a magnetic field. What kind of shield do you have?

Dr. Nicol: Lead. Superconducting lead is fine at present operating temperatures. At the moment, for laboratory purposes, we are using liquid helium at 3.6 to 3.8K.

NAVY USES OF CRYOGENIC SYSTEMS

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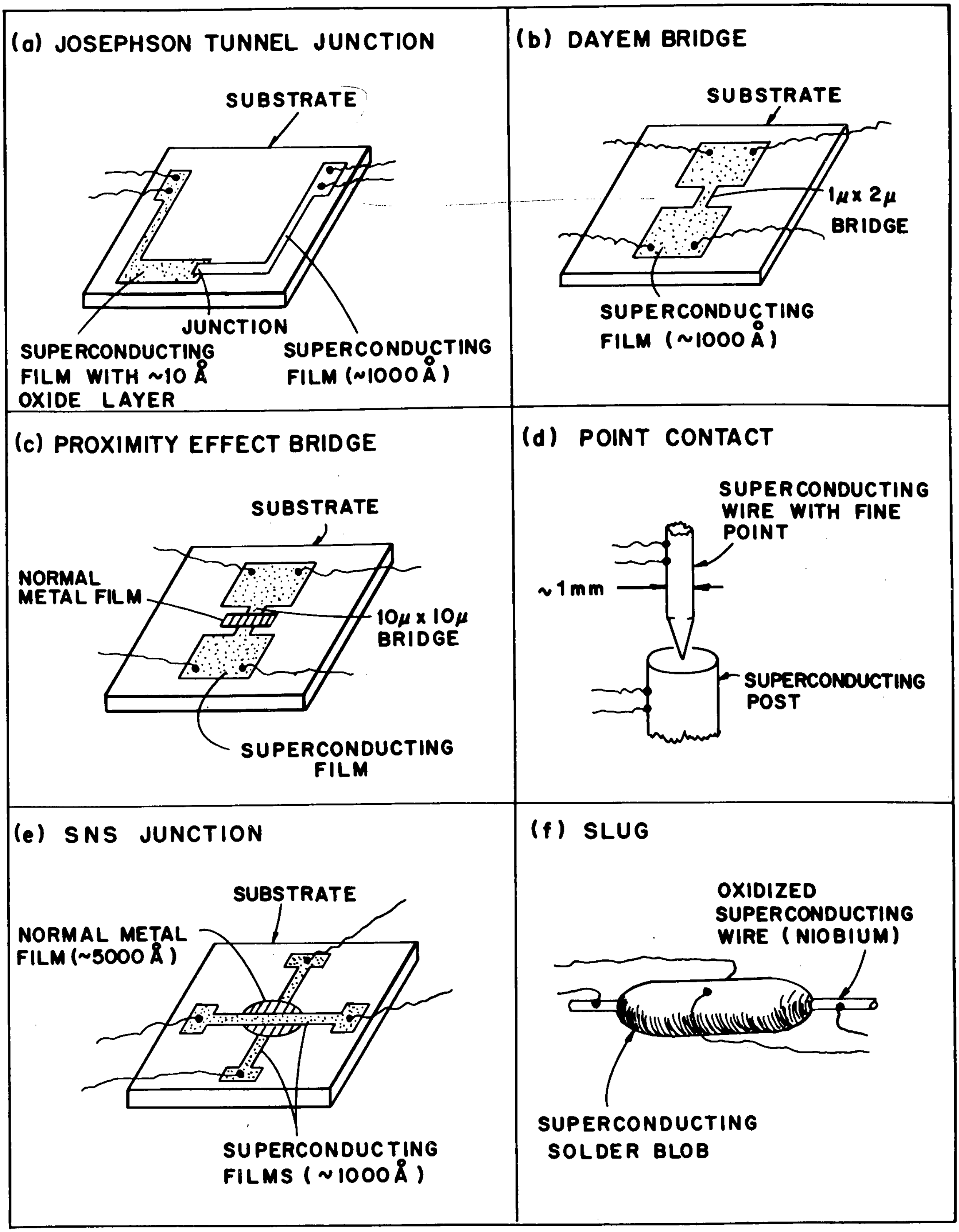
I'm here today as a member of a group which has been taking a look at the question of what cryogenic, in particular - superconducting, technology might do for the Navy. This group includes John Clarke, Bill Little, Jim Mercereau, Paul Richards, Doug Scalapino, Al Schwettman, and myself. What I have to say is going to be based partly on the current thinking of the group and partly on my personal prejudices. If I make any crashing errors, please classify them in the latter category. I am not going to add any facts to those which the preceding speakers have presented so well. What I would like to do is to raise some questions. I don't propose to give any definitive answers to these questions. I'd like to give some opinions about possible answers, but my principal aim is to stimulate the discussion which I think is the real objective of this meeting.

The first question is: "What, if anything, is there in existing superconducting technology which the Navy might use to help it carry out its mission?" I think it is important to realize that this technology spans an enormous quantitative range. We heard yesterday about projected superconducting magnet energy storage capacities of 10^{11} joules. At the other extreme, a back-of-the-envelope calculation shows that the important energies in Jim Mercereau's magnetometers are a few kT at helium temperatures, perhaps 10^{-22} joules. These two numbers bracket thirty-three orders of magnitude in which one can search for useful devices. These numbers and the talks we've heard suggest that we are really dealing with two kinds of superconducting technology. We might call them megasuperconductivity and microsuperconductivity. On the one hand we have the big muscle stuff -- high power, big fields, large volumes -- and on the other hand the most delicate of all imaginable physical apparatus, macroscopic systems in which the important energies are less than the ionization energy of a single hydrogen atom.

With this tremendous range of possiblilities in mind, let us briefly look at what we have heard about what can be done with superconductivity at this moment. We've heard about superconducting magnets, existing magnets, characterized by numbers like 150 kilogauss in volumes like a 6 inch cube. We've seen a picture of the Argonne National Laboratory magnet with 18 kilogauss in a 4 meter diameter and an energy storage capacity of 80 megajoules. We've seen a picture of a projected 50-100 kilogauss magnet for fusion research with 80, 000 megajoules storage capacity. That's apparently just barely feasible now, but it is feasible. We've also heard talk about moving big fields - rotating machinery. Here again, the numbers are large and rather impressive. Machines now exist at power levels up to 3000 horsepower, functioning or almost functioning. Mr. Mole spoke of a weight advantage of 5 to 1 for a proposed airborne 5 megavolt-ampere generator. There are apparently even cost advantages in many systems if you take into account both initial cost and operating costs. It looks as if there is going to be quite a lot of useful megasuperconductivity.

On the microsuperconductivity side, we've heard about a host of devices based on the Josephson effects. Fig. 1 is my own version of the standard picture showing most of the different kinds of Josephson junctions. It includes the Josephson tunnel junction, the Dayem bridge, the proximity effect bridge Mercereau talked about, the point contact, the super-normal-super proximity effect junction, and the slug. These are moderately- to well-understood devices which display weak superconductivity between two coupled superconductors accompanied by a variety of interesting and useful properties. For example, all of them are active non-linear rf and microwave elements, although they differ in some of their detailed properties. Tunnel junctions have relatively large Josephson supercurrents and shuntconductances which are essentially zero. The several types of weak links also have sizeable supercurrents but have appreciable shunt conductances. The geometries vary widely. Some of them have large capacitances and some have low capacitances. Some of


(a) JOSEPHSON TUNNEL JUNCTION
SUBSTRATE
JUNCTION
SUPERCONDUCTING FILM WITH ~10 Å OXIDE LAYER
SUPERCONDUCTING FILM (~1000 Å)
(b) DAYEM BRIDGE
SUBSTRATE
1μ x 2μ BRIDGE
SUPERCONDUCTING FILM (~1000 Å)
(c) PROXIMITY EFFECT BRIDGE
SUBSTRATE
NORMAL METAL FILM
10μ x 10μ BRIDGE
SUPERCONDUCTING FILM
(d) POINT CONTACT
SUPERCONDUCTING WIRE WITH FINE POINT
~1mm
SUPERCONDUCTING POST
(e) SNS JUNCTION
SUBSTRATE
NORMAL METAL FILM (~5000 Å)
SUPERCONDUCTING FILMS (~1000 Å)
(f) SLUG
OXIDIZED SUPERCONDUCTING WIRE (NIOBIUM)
SUPERCONDUCTING SOLDER BLOB

them - the thin film devices - are clearly compatible with the sort of thin film technology which has been developed in the semiconductor game for integrated circuits and of the sort which is becoming more and more important for rf applications - microstrip transmission lines and the like. The interesting rf properties persist to frequencies well beyond superconducting gap frequencies, i.e. beyond 10^{12}Hz. These devices have been successfully applied (in the laboratory) to the measurement of voltages as small as 10^{-14} V and very small magnetic flux of something like a thousandth of a flux quantum, which betters by 3 or 4 orders of magnitude the kinds of sensitivities which can be obtained with other types of magnetometers. We've heard talk of possible sensitivities of 10^{-5} flux quantum and field sensitivities limited only by how large a field magnification you can get with superconducting flux transformers, perhaps 10^{-14} gauss or so. We've heard about detectors of electromagnetic radiation in the millimeter and submillimeter microwave range with sensitivities equal to or surpassing those of existing detectors in this range even though the superconducting detectors have not yet been fully developed.

There is one area which has been omitted in the talks that we have heard. I think it's a significant and important area, so perhaps I can digress for a moment to say a little bit about it. It involves the use of the low-loss characteristic of superconductors to get very high Q elements for various kinds of radio frequency circuits. Somebody yesterday made the remark that superconductors don't really have zero resistance. Certainly at any non-zero frequency, this is so. As most of you know, if you look at the surface resistance of a superconductor as a function of frequency and of temperature - let's plot it as a function of temperature - you get the normal state surface resistance above T_c and then (at relatively low frequencies) it drops off rather rapidly but remains finite and quite measureable down to the lowest temperatures. As the frequencies approach the superconducting gap frequency, the loss becomes higher, and as you get above the gap, the superconductor looks just like a normal metal. At frequencies well below the gap (in practice, this means frequencies up to 10^{10} Hz or 10^{11} Hz or so) the loss is sufficiently small so that it is possible to make rf devices with exceedingly high Q's. At X-band (10^{10} Hz) the Stanford group has reported achieving Q's of 10^{11} in niobium cavities. At frequencies of several hundred MHz, they have reported Q's of 10^9 in niobium cavities. Mercereau has found Q's of 2×10^8 in lead resonators at 30 MHz. These Q's are on the order of 10^6 times larger than you can get with conventional normal metals.

one of the things that was mentioned yesterday is that an important feature of the use of high resistivity ratio metals like aluminum or copper in the construction of magnets is that their resistivities at helium temperatures are much lower than they are at room temperature. At any reasonable frequency, this simply isn't so. One runs into the anomalous skin effect and the very best copper you can get doesn't look significantly better than ordinary run-of-the-mill shop copper at rf frequencies and at low temperatures. So here is something that superconductors can do orders of magnitude better than normal metals, even the best normal metals.

What kinds of materials do we have available to do all this with? Well, we have materials with T_c's ranging up toward 21 K, critical currents up to 10^6 A/cm^2, H_{c2}'s at 400 kG. We have materials with a wide variety of mechanical properties ranging from the very hard superconductors all the way down to the conventional soft superconductors, which for some applications, particularly electronic applications, cannot be ignored. Right here, I feel compelled to put in a plug for at least one soft superconductor. Bob Rose said yesterday that niobium tunnel junctions look like a good bet if you want stable time-independent tunnel junctions. I'd like to suggest lead tunnel junctions as another good possibility. Lead junctions are a lot easier to make than niobium junctions. We've been making them by the standard conventional simple oxidation techniques. Because we are concerned about diffusion, we have stored them at 77 K, but we've used these junctions for periods of up to a year with no visible change in their characteristics. Schroen of Texas Instruments has stored lead junctions at room temperature for periods of up to a year with no significant change in characteristics. So I think there are a number of applications for which one doesn't have to think entirely in terms of high T_c hard superconductors.

To go with the materials we have refrigeration of a sort. For some applications, simply filling a dewar will be adequate. If it is not, continuous refrigeration systems are available if you need them badly enough, if you're willing to pay for them. The efficiencies are low. We heard yesterday of efficiencies of a few percent, perhaps 10%, normalized to the Carnot efficiency. One must remember that the Carnot efficiency in the helium temperature range is about a percent or so, so we're talking about overall refrigeration efficiencies of maybe 10^{-3} to 10^{-4}. With that sort of efficiency, you've got to have a goal that's worth getting to in order to justify paying the re-

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quired price.

With this kind of a bag of cryogenic tricks available, one can ask: "Are any of these capabilities sufficiently closely identifiable with real Navy needs so that the Navy might reasonably decide to move actively to exploit them now?" Well, if you're thinking about a cryogenic system, there is always some room temperature system in competition with it. Perhaps the most promising cases in which cryogenic systems deserve serious consideration are those in which some significant performance parameter is orders of magnitude larger in the cryogenic system than it is in any corresponding room temperature system. We have seen two outstanding examples of such cases. One of these is the case of the Josephson magnetometer. Conventional magnetometers have sensitivities of perhaps 10 to 100 flux quanta and superconducting magnetometers have potential sensitivities of perhaps 10^{-5} flux quanta. What can you do with such sensitivities? In view of some of the facts which Dr. Nicol gave us this morning, it's clear that it is not simply a matter of going out and getting a factor of 10^7 increase in sensitivity to whatever it is you want to measure. But the point I want to make is that with that enormous increase in sensitivity, one very serious constraint on one's ingenuity with respect to possible magnetometer systems has been essentially completely removed. There are undoubtedly other constraints which will dominate long before one actually gets the factor of 10^7 improvements, but at least the sensitivity problem is gone. There remains, as Dr. Nicol pointed out, an enormous number of very poorly understood factors, including the noise problem. But you can now go out and investigate these factors without having to worry about whether or not your sensor is sensitive enough to probe the limits of the thing that you're trying to investigate. Dr. Nicol talked about gradiometers or second derivative devices. One might speculate about nth-order derivative devices, and systems for looking at the independent components of the first derivative and the second derivative in various combinations. One can build incredible arrays of these devices in a very small space. And since one can get enormous amounts of information from large numbers of these devices, one can afford to let one's imagination go a little bit on complex signal processing systems.

That raises the question of large arrays of Josephson devices, something that has not been looked at very much. People have not looked much at systems containing more than one or two Josephson junctions because they have been trying to understand the basic physics involved and there has been no clear reason for complicating things unduly. But now the physics of the devices is well enough understood so that it may well be time to start working on relatively complicated systems in which a large number of elements are superconducting, e.g., arrays of magnetometers coupled to superconducting amplifiers.

The other case where the numbers for cryogenic devices are orders of magnitude beyond the nonsuperconducting state-of-the-art is the high-Q area. Q does not stand for quality factor for nothing. One can imagine situations in which six orders of magnitude improvement in Q might well have very significant consequences - consequences significant enough to warrant going to a cryogenic system with the necessary refrigeration. One of the situations which comes to mind is communications - both transmission and receiving. One needs filters if one has a large number of channels. One often needs very complicated resonant filters and these introduce losses. One can handle kilowatt powers at rf frequencies with superconducting filters with insertion losses which are totally negligible, and with unloaded Q's of order 10^8 or more.

Next, there are some cases in which the improvements which can be obtained from a cryogenic system are not orders of magnitude, but perhaps factors of two or five. These have to be looked at, however, because there are situations where even a factor of two is absolutely crucial. One possible example is a situation in which a factor of two in the performance of a propulsion system in some kind of vehicle might be just enough to make it really effective. In cases like that, a factor of two can be very important. Maybe one can get that factor of two with a superconducting system. Another case where a factor of two is indeed important is in the budget of the DoD. If one could use superconductivity to reduce that by a factor of two, I think we'd all feel a little happier in the pocketbook. Despite that factor of 10^6 or 10^7 improvement that's possible in magnetometer sensitivities, the magnetometer applications may in fact fall in this class of marginal advantage because of other performance limiting factors. But, again, a factor of two or three in, say, range could be very important indeed, especially when you accompany it with the other possible advantages of superconducting systems in information gathering capability, in the kinds of information that you can gather and handle conveniently.

The third question I would like to ask is: "If one does identify some area as being in a state where an intensive development effort might be very fruitful, how should you go about it?" We've also given this some thought. It's clear that one has to begin looking at entire systems, something that the physicists who have been doing research in superconductivity have not done much of. It has been done for large superconducting magnet systems and for large electrical rotating machinery in which the whole environment in which the device has to work must be considered. Less has been done in microsuperconductivity, but it will clearly have to be done because to some extent it will determine what sort of basic research still needs to be done to fill in the holes. When I said the basic physics of Josephson devices was fairly well understood, I did not mean to imply that there are not some holes that need to be filled in before functioning systems can be designed with confidence. As an example, if you look at the capabilities required of a magnetometer system, including refrigeration, low cost, convenience, and that sort of thing, you may very well find that you can save a lot of money and a lot of space if you do not operate at 4 K but at, say, 10 K or 15 K. In that case, you have got to be prepared to build your magnetometer devices out of high T_c superconductors, and there really hasn't been very much work done in that area. In some high power applications you might find that it is absolutely crucial to solve a severe heat transfer problem. There may then be an advantage in paying for extra refrigeration, taking the consequent licking in efficiency, and going down to the superfluid helium range where one has the advantage of an insulating superfluid medium with a thermal conductivity thousands of times that of copper. That may be an important factor in high energy density systems.

"Who is going to look at the systems?" is also an important question. I have the feeling that superconducting magnets have been around long enough to give a significant number of engineers a taste of megasuperconductivity, but I think the microsuperconductivity or electronics region is still pretty much in the hands of physicists. We've looked at the physics, not at the engineering. If we are going to devise working systems based on this sort of thing, we are going to have to couple these physicists either into an engineering frame of mind or to engineers. But in none of these areas, I think, can we really commit the development totally into the hands of engineers, simply because it is still a rather delicate and finicky technology, even at numbers like 80,000 megajoules. For the near future, at least, we are somehow going to have to devise a scheme to bring engineers and physicists working in the area together, if we are to get systems that work, and soon.

One further question which we might consider in the following discussion: "How do we couple academic physicists working in this area into this kind of development?" This is related to the problem of how one handles DoD funded research in universities. It is a small problem now, but it could get to be a bigger problem. As you know, there has been a good deal of debate about this and I don't think there are any pat answers to the question. But, somehow, the question has got to be answered in a practical way if the Navy is to continue making use of the experience and expertise of that segment of the superconducting physics community which happens to reside in academic institutions.

SUMMARY

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Before I open the session to some general discussion, I would like to summarize what has happened up to this point. We have reached the end of the first half of the meeting, and the purpose of this part was to hear the opinions and comments of various experts regarding the current status and the future prospects of superconducting technology and its relationship to Naval requirements. I feel that they have done an excellent job. In a sense, they have been our keynote speakers. They have informed us and stimulated us so that there might be a lively and productive discussion in the second half of this meeting among the Navy participants. I think it is appropriate at this time again to express our appreciation and thanks to our speakers.

In my few remarks, I will summarize and put into perspective the events of the meeting up to this point. The meeting began with a review of the science of superconductivity and was followed by presentations on various technological developments and systems applications. The first point I want to make is that it is now reasonable to talk about all three elements: science, technology and systems applications. There have been sceptics in the not-too-distant past who have proclaimed that nothing practical would ever result from superconductivity, asserting that superconductivity was merely an interesting subject for scientific inquiry. I think there is now ample evidence that these sceptics are wrong. I hasten to stress that the converse is also not true. Superconductivity will not solve all the critical problems of the Navy. It is not a panacea, but we are witnessing the development of a competitive technology which may find its way into various systems applications.

Another point of a general nature, which was brought out in the introductory talk by Dr. Takken, is that there really are two different aspects of superconductivity, each leading to its own technology. First there is the familiar bulk superconductivity most simply characterized by zero electrical resistance. Bulk superconductivity has been exploited in a variety of large-scale applications such as electrical motors and generators. The second kind of superconductivity I will refer to as quantum superconductivity which pertains to tunnelling through a thin barrier separating two superconductors. As you heard many times, quantum superconductivity is the basis of various small-scale devices which can be used as magnetometers and IR detectors, for example.

In order to exploit bulk superconductivity it is necessary to have a superconductor in which zero resistivity is maintained in the presence of large magnetic fields. This is only possible in so called Type II superconductors, but even then we have heard that the magnetic flux lattice can move in response to a current causing dissipation. This dissipation can be eliminated if somehow we can attach or pin the flux lattice to the material so that it cannot be easily moved. These pinning forces apparently result from various imperfections in the crystalline lattice. Thus we have the situation where the best superconductors are the most imperfect, and we heard from Professor Rose the many ways for achieving desirable states of crystalline imperfection. Prof. Rose also revealed that it is more of an art than a science to fabricate superconductors in technologically useful forms. However, through diligent efforts such difficult problems as thermostabilization have been largely solved and today we have a wide variety of satisfactory superconducting materials which are available commercially. These materials are suitable primarily for dc applications. The state-of-the-art with regard to materials for ac applications is much less advanced. Prof. Rose also speculated that materials with transition temperatures as high as 30 K would be discovered in the not-too-distant future. We hope that he is right, because such a significant increase in transition temperature would translate into substantial systems advantages.

The extent to which bulk superconductivity has been exploited in large-scale machinery was reviewed by Mr. Mole. There is indeed an impressive number of projects in many countries concerned with superconducting motor and generator development. Several dc machines are nearing completion with very favorable operating characteristics expected. Most notable in this group is the 3,000 horsepower motor being tested in Great Britain. Although fewer large ac machines have been constructed, there is considerable activity in this area as well. In the United States a four MVA generator is expected to be completed at MIT in mid-1971. Mr. Mole also mentioned a study performed at Westinghouse which convincingly demonstrated the substantial size and weight advantages expected for an ac superconducting power plant in the 5 to 7 MVA region. These advantages make such a device particularly attractive for airborne applications.

The construction of superconducting magnets is probably the most technologically advanced application of bulk superconductivity. Dr. Coffee reviewed the many technical problems faced by the magnet designer. One of these problems is material strengths at 4 K since the superconductor must withstand enormous magnetically induced stresses. However, these problems have become manageable as experience has been acquired with certain superconductors such as niobium-titanium. But these same problems will have to be faced again as new materials are put into use.

Now I'd like to turn to the subject of quantum superconductivity and its applications.

The basic phenomenon which can be exploited is the dependence of tunnelling current on electromagnetic parameters. Professor Shapiro showed how the Josephson currents behave when both a dc bias voltage and an rf voltage are impressed simultaneously. The interaction of the induced ac currents with the impressed field leads to a series of steps in the current-voltage characteristic. When the system is coupled to a cavity there is also an interaction with modes of the cavity. These various interaction effects can be exploited in several ways to build radiation detectors with impressive characteristics. These detectors can either be wideband or narrowband depending on the circuit configuration, and the response time and sensitivity are comparable to or better than the best currently available competive devices in the far infrared.

Prof. Shapiro conservatively estimates that superconducting IR detectors may be abailable commercially in 5 to 10 years. He foresees a perfectly engineered device in which the efficiency of radiation coupling is optimized and the superconducting material has been selected to enhance the response at mid-IR wavelengths.

Superconducting magnetometers also appear to have an exciting future based on the review given by Dr. Goree. He showed that the best non-superconducting magnetometers have field sensitivities which are generally one or two orders of magnitude less than those of superconducting devices. Furthermore, the superconducting magnetometers have considerably more growth potential remaining and should ultimately have far superior operating characteristics. The very small volume of the detection region also appears to be an asset which has not been exploited. Although the superconducting magnetometer design discussed by Dr. Goree was based on flux quantization and bulk superconductive properties, numerous Josephson-effect magnetometers can also be constructed. Prof. Mercereau in his talk this morning described some of these various types of Josephson-effect magnetometers. He also created the impression that the technology of the construction is well in hand; there are a variety of ways to make reliable and stable devices. Furthermore, he made the optimistic prediction that a sensitivity of 10^{-14} gauss might ultimately be achievable with a superconducting magnetometer.

The work reported by Dr. Nicol is concerned with the development of a prototype sensor package for making sensitive magnetic field measurements. This project represents an attempt to construct actual test hardware in the form of a magnetic-field-gradient detection system. However, one critical question remains before the full potential of such a system can be assessed. Namely, does the magnetic noise environment prevent the full sensitivity of the instrument from being utilized? This question can perhaps be answered in the near future because test equipment of the type described by Dr. Nicol will become available over the next few years. It is imperative that equipment of this type by used to perform actual field measurements. Only when the magnetic field environment is adequately characterized will systems applications studies become truly meaningful.

The same theme was repeated in the presentation of Dr.

Langenberg. Although he listed several areas where superconducting technology might have an impact, the general feeling was that it would be difficult to quantify such arguments because of the unavailability of critical data. One area again is the lack of information concerning magnetic noise background. This doesn't mean that nothing can be done; it certainly is possible to perform parametric studies by making assumptions about unknown quantities, and we do hope to see systems studies of this type performed in the near future to try to answer some of the questions that Dr. Langenberg raised. The time is ripe for systems thinkers to evaluate the present and future prospects for superconducting technology. A number of speakers have mentioned refrigeration. This, of course, is a necessary subsystem in any superconducting system. In a real operational environment the refrigeration subsystem must be rugged and simple to operate and service. As mentioned in Prof. Daunt's talk, much development work is still needed to achieve these objectives of reliability and maintainability. Another goal would be to improve on operational efficiency, which is only a few percent of Carnot efficiency at 4K. With such improvements, substantial reductions in weight and volume would also accrue, and this would be favorable for systems design. Nontheless, it is still rather amazing that even with present-day, relatively inefficient refrigeration subsystems, superconducting technology still looks promising in some systems applications.

In conclusion, I would like to say that we have seen during the course of this first day-and-a-half that there is a vigorous superconducting technology which has developed because there is a firm foundation of scientific knowledge. Using this new technology, various devices and systems components have been constructed, and these have unique operating characteristics. It is a challenge for the Navy and others to make the best possible use of these new capabilities in various systems applications.

This concludes my remarks, and I would like at this time to open the session for discussion. I realize that there will probably be some questions which can't be raised at this time because of security restrictions, but I think there are many questions which can be brought up, and this is the last time our excellent cast of invited speakers and the many Navy personnel will be together. It needn't be a one-way dialogue with only the assembled group of experts permitted to respond to questions; we hope that questions will be addressed to the Navy personnel as well and that a lively discussion will develop.

QUESTION SESSION WITH INVITED SPEAKERS FORMING A PANEL

Dr. Hanrahan, NRL: In connection with the high Q-circuits, as you come down from the microwave frequencies, a realizable Q falls off and the circuit size increases. Would you eventually guess that a frequency below which a superconducting circuit would not be worthwhile?

Dr. Langenberg: If the loss is entirely due to the thermally excited normal electrons in the superconductor, then the Q's ought to scale as $f^{3/2}$. That is, the Q of the superconducting resonator relative to the Q of the normal resonator goes as $f^{3/2}$, so the Q differential at very low frequencies is less than it is at high frequencies. However, I think it is difficult to say anything very specific about what sorts of Q's you can get at very low frequencies until you actually try to build something. The principal reason is that what appears to limit the Q's that everybody has seen so far (most of the work has been done at high frequencies) is the residual resistance. If you ask what that is, I think the answer is that nobody really has any idea. You can follow the resistance down with decreasing temperature at any frequency you care to name, and down to a point it follows the theoretical calculations of Mattis and Bardeen for what ought to happen for the resistance of a superconductor. Then it bottoms out. The residual resistance is often considerably higher than the resistance you would calculate for the ideal superconductor at the same temperature. It appears to have considerable connection with surface finish in the resonator or high-Q system, and probably has to do with the motion of fluxoids. It has also been suggested that it may have to do with the generation of phonons at cracks and voids in the surface. It's a pretty complicated business and I'm not even sure anybody knows what the frequency dependence of the residual resistance is over any wide range. So I think the answer to your question is, "If you want to know about what Q's you can get at very low frequencies, build a resonator and see."

Prof. Rose: You know, a while back we made some tunneling measurements on single crystal niobium and found it had an extra energy gap. And the extra energy gap is roughly a tenth of the energy gap

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corresponding to 9.2 K. At this point, of course, when you start constructing radio frequency devices (and we have been fiddling around with superconducting helical resonators and things like that) you begin to wonder, because above the order of a few gigacycles - the second gap frequency - you're in trouble. At these frequencies you should be exciting superelectrons across this extra gap of niobium and getting a lot of absorption. We know the gap is there and I can only tell you that I suspect that you have to get your surface clean but not so clean that you see the extra gap. So, perhaps it's even more of a black art than you might expect as far as surface preparation is concerned. Quite honestly I'm frightened by the whole thing.

Mr. Dickenson, NAVEODFAC: I'd like some comments on the possibility of getting high T_c organic superconductors. I believe a number of people are working in this area and some people are very optimistic and some people are very pessimistic.

Dr. Takken: There has been considerable interest in organic superconductors for several years now. Rather than make extemporaneous comments on the topic, let me defer to the forthcoming RAI study being done for ONR. In that report, Prof. William Little devotes a chapter to organic superconductors. I feel sure that most of the questions pertaining to thin topic will be answered in that reference.

Dick Harris, United Aircraft: Certainly no one would have any gripes about a high temperature superconductor but I would like to say something that I think has been implicit in this conference and is implicit in the interest in applying superconductivity that's become apparent recently. That is, the present technology is going to be used in an economic way to make commercial machines without developing superconductors having higher $T_{c's}$. In the large machines it isn't even necessary now to use Nb_3Sn. Niobium titanium is quite adequate. In the microdevices that the later speakers talked about, they are talking about using materials which have substantially lower $T_{c's}$ than the larger machines will use. I think the point to make here is that these machines are going to be usable and their going to be economical even with the materials we have now and I think that's the really exciting thing about what's going on here.

Dr. Langenberg: I would just like to comment that I second that most strongly. It's my personal view that the day when you can have your megnetometers built by trained bacteria is far enough off so that I think you ought to build some right now yourself!

Dr. Lehmberg, NADC: A question for Prof. Daunt about the feasibility or even possibility of remotely cooling a system at a distance of, say 150 ft, by putting superfluid helium through a more or less flexible hose perhaps a couple of inches in diameter. Is this within the realm of possibility that we could have completely remote cooling of this type?

Prof. Daunt: Certainly. I think this is quite possible.

Dr. Brandt: What is a flexible material at 2 Kelvin?

Prof. Daunt: One already has flexible transfer tubes made out of stainless steel bellows. I'm not quite sure whether the question was whether the hose should be flexible at liquid helium temperatures at 2K or whether it should be flexible and then operate at that low temperature in the position to which you have flexed it. Perhaps you would enlarge on that question.

Dr. Lehmberg: It must be able to pass the superfluid helium and still be flexible. This is really the question.

Prof. Daunt: I partially retract my previous remarks then. There are some materials which one can flex at liquid helium-for example mylar, lead and stainless steel bellows and so on - but its not immediately obvious to me that these can be developed into systems such as you're thinking about without quite a considerable amount of work.

Prof. Webb, Cornell Univ.: We have transferred helium into a Dewar containing superfluid helium below the Lambda point and it is a simple trick. You can just pass normal helium through any transfer tube and let it dribble through an orifice into the Dewar which is being pumped. Also, there are flexible stainless steel bellows that work fine over 10 or 12 feet and there is no reason why the same flexible bellows would not work at 2 degrees Kelvin. I think you don't have a serious problem here.

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Prof. Daunt: I would question that. I question very much whether one can flex stainless steel bellows at 2 degrees and not have any long range problems. It all depends on the total number and the frequency of the flexings. I remember some years ago Prof. Simon worked on a helium liquifier in which the expansion engine consisted of such a stainless steel bellows. Although it did work, it had a limited life (approximately 10^6 flexing per bellows). I would maintain that there is still development effort to be made on this question if one is considering a substantial number of flexings.

Mr. Stuart, Cryogenic Technology inc.: I feel a little bit out of place since I'm the only refrigeration representative here. To me this suggests that Dr. Langenberg's previous comment calling for further interaction between the physicist and the engineer is a very valid one.

With respect to the particular question, work on bellows at low temperatures has been done at MIT, with encouraging results. Bellows engines have been operated now for millions of cycles, well beyond the endurance limit, suggesting that it is quite possible to get flexible items to operate for long periods of time at cryogenic temperatures.

I would like to enlarge upon Dr. Langenberg's comments regarding the need for further communication. Some of the comments made in this conference suggest that refrigeration is something that you would all rather avoid. However, we must work together because our future is tied together. Unless the refrigeration people are successful, then your work will not be successful. Similarly, unless the physicists succeed, refrigeration companies will fail. We will disappear to the bottom of the ocean together. Therefore, it is important that we work together and that we communicate. Gross simplications can be inaccurate. For example, the Carnot relationship is a useful relationship for estimating refrigeration power. However, the efficiency with respect to Carnot is quite variable. As Dr. Daunt pointed out the 1.8°K Stanford refrigerator is very efficient. The good performance results from a discontinuity in the efficiency curve which means that units operating below 4 degrees will generally be more efficient with respect to the Carnot ideal than those operating at 4 degrees. Other similar problems exist. For instance, weight curves typically are developed based upon laboratory equipment. One can get an order of magnitude improvement between units designed for a specific application, and those designed for the laboratory. There are similar discontinuities with cost. At the moment, 77°K refrigerators designed for airborne use are more expensive than 20°K refrigerators for similar service. The costs relate to the numbers of units which have been suilt. The high cost differentials between 4°K and 20°K systems are more a function of the number of units built, rather than the complexity of the task. Discontinuities of this type are going to lead to systems studies coming up with results which are not correct.

I am interested in your work. That is the reason I am here. Our future depends upon understanding what is going on. I would like to give credit to Mr. Edelsack of ONR for starting work in the direction of resolving the refrigerator/device interface. I can only plead that others follow his lead and hopefully, we can both benefit by a better exchange of information.

Dr. Klick, NRL: I was wondering if I could ask someone, either Profs. Mercereau, Shapiro, or Langenberg perhaps, to comment a little bit more on something which was only alluded to today - superconducting amplifiers. It seems to me to be fairly crucial in many of these applications to have a low temperature amplifier as part of the electronics.

Dr. Langenberg: Perhaps I could volunteer, although I know very little about it. We've just begun to look into some of the possibilities and other people are looking at the possibilities, starting simply from the point of view that they've got a low temperature device, a sensor, and they've been working with room temperature amplifiers. They're now really interested in pushing the sensor down to its ultimate limit and it's clear that they have to get some gain at low temperatures. What are the possibilities? Semiconductor FET's work at low temperatures but have terrible noise characteristics. There really isn't anything good that I know of except possibly versions of some of these superconducting devices themselves operated as amplifiers. There's the cryotron amplifier which has been around for some time but hasn't been looked at carefully in connection with Josephson devices so far as I know. It seems to have some promise. I can't quote any performance figures because I don't have any.

Prof. Mercereau: The kind of performance figures that I was talking about this morning are performance figures based on the assumption that your power gain is all done at room temperature, i.e. that the superconductor generates a certain amount of power and you detect that power with a room temperature amplifier. The number that I was quoting is a number that is based on that presumption. If you can get gain at a lower temperature, then of course you get a higher sensitivity, but as long as you're stuck with power gain at room temperature then the number that I gave you is not only an estimate, it's the best you can possibly do. I was also talking about a special kind of quantum device this morning where the barrier ecentially was a metallic barrier to which you can attach leads, and one of the things that we're working on is exactly this possibility of building a superconducting quantum amplifier-if you like-by modulating the gate with an additional current. It looks promising; I can't give you anything but a guess that we will be able to get power gain out of the kind of device that I was talking about this morning.

Prof. Webb: You may be getting more detail than you wanted in answer to your question, but I'd like to mention two things that have been going on at Cornell. First, several of my colleagues have been using low temperature superconducting electronic devices in the radio frequency region and find about a factor of 10 decrease in the noise from high impedance sources. In some of our own work at essentially dc frequencies we use a superconducting device that we call a femtovolt amplifier with which we've been able to push the noise power down to kT at 4.2 degrees. We are easily seeing voltages down to 10^{-15} volts with a one second averaging time. So, indeed, with superconducting systems at low frequencies you have the capability that's theoretically available. However, at higher frequencies I think we have a long way to go. I agree with the previous speakers that there is a lot of room for improvement but I think that it's feasible.

Prof. Shapiro: I'd like to make a few more comments on the superconducting amplifier question. One is that superconducting amplifier question. One is that superconducting amplifiers have been around for a long, long time and the Edelsack/Goree bibliography series contains in every issue a few more pertinent references on the subject. Much of the work has to do with rf in the sense of megacycles and even lower frequencies. I think that that's very valuable and very important. But I did mention yesterday that in the frequency conversion effects at high frequencies we have reason to believe we will find a mode of operation where we can get frequency conversion gain. There will be other modes of operation where we will of course have to take conversion loss. So I'm looking towards microwave type, millimeter-wave type amplifiers also.

Dr. Hein: I am going out of my area of competance, but when one deals with the high-Q circuits, isn't there a "quenching" phenomenon? For example, when one starts to load these cavities they can be driven normal and I'm told that if one calculates the magnitude of the current which is flowing, it is lower than the critical current. There was a statement made earlier that the physics of devices are well understood. I'm curious as to whether or not one understands the "quenching" of these high-Q cavities.

Dr. Langenberg: I don't have direct experience with this but I do remember looking at some of the Stanford reports in which they looked at this effect and found that the quenching occurred at a field which was essentially the critical field for the superconductor, the dc critical field for the superconductor. There wasn't anything peculiar going on. In fact they were a bit surprised because I think they had some mechanism which they thought might have quenched it earlier. But it didn't appear, so apparently things are not so bad.

Prof. Mercereau: I think whether or not its quenched by the magnetic field depends on the material, because in some materials, you actually reach the electron emission field. That is, the electric field limit occurs before the magnetic field limit.

Mr. Karamargin, NUSC: I'd like to ask anyone is it possible that we could -- would ever run out of helium?

Dr. Daunt: I don't have all data at my finger tips on this I regret to say, but steps have been taken to conserve helium a great deal that previously was being wasted by the natural gas industry by just permitting the helium to go out of the chimneys of the furnaces using natural gas and this a very considerable amount of helium. I apologize I don't have a current figure, but as of about a year ago conservation of helium was a long way ahead of consumption. However, I think in projecting these figures it looks as if we may be in considerable trouble twenty or thirty years from now. It may well be that we'll have to make a serious effort to persuade the federal government to take further steps in the conservation program.

Dr. Takken: Although present sources of helium are dwindling and no major new source has been discovered in the last decade-and-a half, the U. S. continues to hold the entire world supply of easily processable helium from natural gas wells.[1] Present proven supplies, in wells of greater than 0.3% helium, are 165.3 billion ft^3 with another 24.6 billion ft^3 probable. In 1968 the U.S. used 2.3 and stored 2.4 billion ft^3 of this helium while losing another 3.6 billion ft^3 in the natural gas used for domestic fuel. Forecasts predict that the U.S. supply of easily processable helium will be consumed before the year 2000.

Of course, one can always hope for new discoveries of gas containing a reasonable concentration of helium. In order to evaluate this possibility it is necessary to quote the figures for natural gas and hence crude oil supplies. While the proportion of natural gas to crude oil discoveries has been reasonably constant, the proportion of helium to natural gas has been, at best, an erratic function of time. Starting in 1917 there were considerable finds in the area bounded by Texas, Virginia and Michigan, but no major helium supplies have been discovered in the last 27 years. However, it is only fair to assume that helium will comprise a non-zero portion of the natural gas supplies to be discovered in the future. The point here though is that the U. S. rate of discovery of crude oil peaked out in 1956 and is now well on its way down the decreasing side of a Gaussian distribution with a width at half maximum of about 47 years. Thus future discoveries of adequate helium supplies are unlikely.

Navy conservationists will probably try to hold onto their 1912 oil-field holdings now being considered for commercial use and might even be interested in import quoted increases. It appears to me, especially now that we are exploring navy applications of superconductivity, that helium supplies also relate to our national security. Perhaps the Navy should consider playing a role in the financially troubled helium conservation program.

1. The 35.3 million ft^3/yr produced in the USSR comes from wells containing some 0.05 to 0.07% helium. See the proceedings of the Helium Society Symposium Proceedings 1970, 1735 K Street, N.W., Suite 700, Washington D.C. 20006.

2. The oil production cycle follows the same time distribution except that it lags behind the discovery cycle by about 12 years. The maximum in the world discovery cycle is projected to occur in the mid - 80's to mid - 90's. See M. King Hubert in Resources and Man, Committee on Resources and Man, Preston Cloud, Chairman, National Academy of Sciences, National Research Council (W.H. Freeman and Co., San Francisco, 1969).

Prof. Rose: One casual comment as a metalurgist: You know the Navy and a lot of other places are prime customers of MIG and TIG welding (Metal inert gas and tungston inert gas welding) and you can do this in helium or you can do this in argon. This is an interesting choice in view of the new uses you are finding for helium.

Dr. Langenberg: Another perhaps related question: Has anyone checked the niobium supply lately?

Prof. Webb: I'd like to add one other comment on this helium problem, without having any numbers, unfortunately. I hope its evident that we can't conserve helium in the same sense that we can conserve fossil fuels. Helium comes out of the ground in natural gas; if the natural gas is consumed without having the helium extracted from it and saved, that helium is lost forever to us without having been used at all because the helium is lost to the earth's atmosphere when it is discharged. The conservation program that Dr. Daunt referred to is a project of the Bureau of Mines. It is my understanding that the Bureau of Mines runs a separation plant which separates the helium from natural gas that then goes on to be used as fuel. The difficulty is that conserved helium gas that exceeds the immediate demand then appears in the Bureau of Mines budget as a cost since it does not contribute to recovery of the cost of operation of that plant. The excess gas is pumped back down into depleted gas wells. My understanding is that this is a major item of the Bureau of Mines operating budget and that the operation is in serious jeopardy. It might be worthwhile for people in the Navy who foresee enlarged utilization of helium in cryogenic devices to try to wield their bureaucratic power to save this conservation program.

Dr. Hein: This question of helium conservation is the main concern of a recently formed group known as Helium Society of America with Scott Carpenter as its president. Congress is apparently concerned.

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Sure we are putting helium gas back into the earth but it is costing the U.S. Federal government one heck of a lot of money. The fact that the U.S. government pays private industry to separate the gas and pumpt it back into the earth, while industry sells helium gas for less than the government does, has caused some rather valid questions. It's strictly a financial matter. Everyone agrees that helium gas should be conserved but who should pay the cost of conserving it.

Dr. Klick, NRL: In the last few years, there has obviously been serious problems with university-DOD interaction, cooperation, and so on. I'm interested in the university comments on this sort of problem in general, but more particularly whether your feeling is that an organization like RAI is in any way a step towards resolving these problems.

Prof. Mercereau: Well, yes I think ours is an attempt to make a step toward resolving this problem in a very restricted area for a small group of people. I think, at least from my point of view that I couldn't do for the Department of Defense as a representative of Cal Tech what we're doing now. I think this is true of everybody that's in the organization. There are some of us who are concerned about the problems of the Department of Defense, and most of our university regulations are such that we can't work on classified problems at the university. Whether or not we're a representative of the university, we can't operate on the campus. So yes, we think it's a partial solution.

Prof. Shapiro: There are of course other mechanisms that have been in operation for quite a few years. There are laboratories that have affiliations with various universities and it has been possible to have at least some of the work in these laboratories on a classified basis. I might say that there are still a few universities in this country where this kind of affiliation can be maintained. And do not overlook the fact that one of the best couplings between physicists and engineers, no matter what the problem is, is on a one-to-one basis, and there's this same old standby we're all familiar with for many, many years and that is plain ordinary, old hard work consulting.

Prof. Rose: I think MIT is similarly situated; speaking just for myself, I think you can paraphrase Mark Twain and say that rumors of our death have been greatly exaggerated. In general, if you believe in what you're doing and the kids know you believe in what you're doing, I don't think there will be any difficulty and there hasn't been any difficulty this year. (I suppose if you're in a real bind you can remember the voltage is too low to hurt!)

Prof. Shapiro: One additional comment here is that we get quite a bit of flack from our engineering students that they don't get enough design and in listening to all the design problems that have been worked upon and still remain to be worked upon in the area of superconductivity I'm certainly going to go back and try to get some of these guys involved as part of their academic program in getting their framework and attitude and orientation towards these kinds of design problems stimulated.

Dr. Langenberg: I think Bob Rose is right with his quotation from Mark Twain, but I would remind you that there remains a possibility, at least on some campuses, that a kind of nonlinear effect involving precipitous action on the part of various faculty and student groups followed by precipitous reaction from DoD could very well cause difficult situations. I don't think it's going to happen everywhere, I don't think it's going to happen generally, but I think it may still happen in some cases. It may happen in just the cases where you can least afford to lose some of the expertise embodied in the scientific part of those universities.

Dr. Brandt: I mentioned the possibility that maybe someone from the panel would like to pose a question for the audience to reverse the stream. Does that possibility exist? Does anyone up here have a question they would like to address to an organization in the audience?

Dr. Langenberg: Let me repeat the question I posed earlier, which is essentially the question we just discussed. What does the audience think is the optimum mechanism to solve the problem that we've been facing here at this conference, namely, to solve Navy problems using superconductivity as quickly and inexpensively and effectively as possible?

Prof. Webb: I think I should reply since I've been shooting off my mouth about this problem. First, it seems to me that this is an extremely useful conference and that the people who organized it really ought to be congratulated. But, the fact is that the reason we are here is that in the field that we're talking about, Navy support has squeezed a lot of science out of a small group of interested scientists. The

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point is that there are some important results from this basic research and these are potentially very useful, to the Navy. Now you're facing the problem of how to get something useful to the Navy out of them. One of the difficulties is getting people in the Navy laboratories exposed to these new results and that's happening right here, I think. It seems to me that it would be interesting to have some of the Navy people tell us or tell the speakers how they feel about what they've had to say; tell the speakers whether you think that they have really put forward any opportunity that can be used. But now for the real question that Dr. Langenberg asked: "How do you get something going?" It seems to me that the one thing that makes sense to do is to try to pull together a couple of pilot projects in the "macrosuperconductivity" effort. I gather from remarks (most of which must be buried in the classified part of this conference) that there are big machines being built and that they are really well along with designs on the way and all that sort of thing. In the "micro-superconducting" field, I gather (without knowing much because of the classification barrier) that you're at the stage where it's about time to try out a development project. But it appears to me that there's a lot of fragmented effort in various Navy labs. Maybe what you ought to do is to pull together a pilot project with the people in the Navy labs who are really interested in these sorts of things and try to solve one of the problems that you Navy people recognize. By putting a substantial a amount of effort on it instead of piddling on the same scale that we do' in the universities you could mount a really coordinated effort to try to make a system go.

Dr. Goree: This meeting has given the speakers the opportunity to present to the Navy a discussion of superconductive devices. To a large extent, this has been a one way discussion - it is up to you to fit these devices to Navy problems. In many cases, we could possibly assist in matching present and potential superconductive devices to Navy needs if we had a better understanding of the problems. Of course, security classification and need-to-know requirements will always restrict a free exchange of information, but I feel it would be worth the effort to work within these restrictions and present us with at least a summary of Navy problems where superconductive devices may be applicable. I understand that a complete discussion of Navy problems will be presented during the classified sessions of this meeting. Possibly a summary of these proceedings, at least listing the Navy groups most interested in the various applications of superconductive devices, would be a good start toward removing the communication gap.

Dr. Lehmberg, NADC: This is really the point that I was going to bring up - this communication gap. The fact is that I have some classified information and there are people here from industry and universities who have the clearance to hear this, but who are going home today. So right here there is a difficulty that there's not going to be the type of interaction that should take place.

Mr. Edelsack: I think Bob's right and I think perhaps one of the things this meeting has accomplished is that it may serve as a useful coupling between, for example, your interests and the people at the academic and industrial community who would like to couple to you. So while now we have focused on where the interests lie, you may be right that subsequently a one to one coupling or some small group might get together to focus on these problems.

Mr. Chaiken, NAVSHIPS: One of the problems with the classified portion is it's an in-house type of thing where the technology in itself may not be classified but what our plans are and perhaps even financial considerations can be classified. This is what makes it very difficult to establish need-to-know. I think Ed might well give consideration to publishing a classified document based on the mixed session, with the unreleasable items expergated. I think it would take a little work but I think it might be feasible.

Mr. Edelsack: Our intentions are exactly to do that. The technical part of the classified session will be available. We will delete some information of a management nature which I think will be privy only to people in the Navy.

Mr. Chaikin: I'd like to go further with one other thing: that's this question of how you get something started? We within the Navy or anywhere within DoD sometimes wonder ourselves. There is no one way, and there is no easy path. This one to one situation is probably still the most successful means. Why? Because even with the Navy group here we all have different interests. If you would try to select one application to foster superconductor technology you'd have a very difficult time picking "the one". I suspect you probably will do disservice to both the technology and the Navy by trying to do this type of thing. I think what has come out of this meeting is that the fact that one more attempt has been made to make one group aware of what is going and what are our potentials. I came here with a prime interest in propulsion. Yet I have a few other irons in the fire. Some of the things I've heard here in the electronics area have started a few wheels going in my head on something which I probably would have never thought back to. In fact, it goes back to looking at something that we looked at ten years ago, which might now become possible. This is totally unrelated to propulsion. So I think, and I suspect that I'm not alone in this kind of a thing, that this meeting can be successful in many secondary ways such as this.

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SESSION F

Thursday Afternoon, 5 November 1970

Chairman: C.C. Klick
Naval Research Laboratory

Session F Contained one paper classified SECRET that appears in Vol. II of the Proceedings

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SUPERCONDUCTIVITY RESEARCH SUPPORTED BY ONR

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I will briefly review the efforts of those groups in ONR supporting research in superconductivity. There will not be sufficient time to describe many significant details but I hope that this short recounting of the several projects will serve to highlight the belief of many in ONR that superconducting technology will play an important role in the future Navy. The genesis of a number of these present day projects date back to the late 1940s when the ONR Physics Program was the focus of all superconductivity and low temperature physics in the U. S. Today there are six separate groups in ONR that support research in superconducting materials, devices and systems at universities, companies and government laboratories. In the calendar year 1970, over two million dollars was spent by ONR in this field - about half the total amount spent in DoD in superconductivity.

Naval Applications and Analysis Division

During the past day and a half you have heard about some of these programs. The work reported by Dr. James Nicol on magnetic anomaly detection is supported by the Aeronautics Programs group of the Naval Applications and Analysis Division. Commander Eugene Doering is project officer in charge of this work (NR 220-032). In the same division, the Naval Analysis group supports a project under the direction of Mr. Ben Friedman aimed at reviewing superconducting technology in terms of future Navy needs (NR 274-110). Mr. Friedman is also supporting an analytic study at the Argonne National Laboratory on the coupling of MHD systems to superconducting motors, generators and propulsion systems (NR 274-109).

Materials Sciences Division

In the Materials Sciences Division, the Metallurgy Program, under the direction of Dr. W. Rauch supports a group at M.I.T. headed by Professor R. Rose (NR 039-087). He is measuring the superconducting properties of niobium, rhenium and various transition metal alloys by observing the electron tunneling behavior in superconductor oxide junctions.

Physical Sciences Division

Each of the three programs in the Physical Sciences Division support research in superconductivity. The Electronics Program under the direction of Dr. A. Shostak supports several superconducting device efforts under the Joint Services Electronics Program. They include research at Harvard University on ultrasensitive magnetometers (NR 372-012) and at the University of Southern California on the measurements of the superconducting energy gap of Nb_3Sn (RR-008-02). At the University of Texas, Professor William Hartwig and his colleagues have developed a series of superconducting resonant cavities for measuring the electrical properties of various superconductors over a wide radio frequency range (RR-008-05).

The biggest single effort in superconductivity research in ONR is in the Nuclear Physics Program under the direction of Dr. Doran Padgett. Dr. Padgett is supporting at Stanford University a large group under Professor William Fairbank (NR 023-026) who are designing, building and testing the first large scale, low temperature facility of its kind in the world. This system, when completed, will include a 500-foot long cryogenic test bed of superfluid helium, continuously cycled to a 300 watt helium refrigerator operating at 1.85 K. The ultimate goal of this project is to build a 2 to 10 billion volt superconducting electron linear accelerator for high energy physics research. This accelerator will be under the management of the National Science Foundation. The accelerator will consist of 500 feet of superconducting niobium microwave cavities operating at 1300 MHz. The significance of this sizeable project to the Navy lies in demonstrating the potential of large scale cryogenic systems operating at liquid helium temperature aboard ships.

The last effort I would like to describe is in the General Physics Program under the direction of Mr. Frank Isakson. It is the "Superconducting Elements Program" and has as its goal the exploitation of the unique quantum properties of superconductors for the development of advanced instrumentation and measuring techniques. Some of these superconducting devices represent improvements of several orders of magnitude in sensitivity over existing technology. Research on the following types of devices is being supported by this program: ultrasensitive magnetometers and magnetic gradiometers, millimeter and submillimeter wave detectors, microwave circuit elements and parametric amplifiers. The following is a listing of those tasks presently being supported:

1. Professor B. Rosenblum at the University of California at

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Santa Cruz (NR 319-006) is studying the microwave properties of bulk and thin film Type II superconductors such as lead-indium alloys. He is interested in the mechanisms by which flux tubes are immobilized by metallurgical defects. Impedance measurements of the flux pinning in thin films and by surfaces at frequencies from one to several hundred megacycles permit study of the concept of "pinning potential". This concept appears useful in describing the nature of rf losses.

2. Professor A. van der Ziel at the University of Minnesota (NR 319-011) is investigating both experimentally and theoretically the various noise sources which limit the sensitivity and stability of various classes of superconducting devices. In particular, he is studying thin foils of Type II superconducting materials such as vanadium, thin cylinders of Type I superconducting materials and point contact Josephson junctions. He has built stable point contact Josephson junction type amplifiers which operate at 30 MHz and can detect low frequency noise down to 10^{-26} Volts^2/Hz.

3. Professor S. Shapiro at the University of Rochester (NR 319-012) is studying the properties of superconducting devices as sources and sensors of microwave and millimeter wave radiation. He is investigating the varied phenomena resulting from the coupling of a Josephson junction device to a cavity, resonant at one frequency and simultaneously driven by an external radio-frequency source at a different frequency. He is also investigating portable Josephson effect infrared detectors operating in the 3 to 30 GHz range.

4. Dr. M. Nisenoff of Stanford Research Institute (NR 319-017) is investigating the properties of thin film circuits of niobium and niobium nitride. These circuits are to be used in the construction of a superconducting magnetometer operating in the 10-20 K temperature range.

5. Professor T. Smith at the University of Southern California (NR 319-020) is studying the linewidth of the radiation emitted by a Josephson junction when biased with a thermocouple voltage source. A superconducting transmission cavity and a frequency sensitive element in a receiver will allow detection of the emitted radiation with a resolution of 1 part in 10^{10} at X band.

6. Professor J. Mercereau of the California Institute of Technology (NR 319-021) is studying the behavior of thin film crossed-strip structures containing one superconductor and one normal metal. Films of tin-gold, lead-copper and indium-copper have been

used. These weakly superconducting devices have been incorporated in both active and passive superconducting devices. The following have been fabricated and are being studied: (a) thin film single and double junction interferometers, (b) superconducting antennae incorporating a weak-superconductor section as a detector and (c) high Q superconducting cavities incorporating a weak-superconductor section as a drive oscillator. The problem of interfacing a miniature closed cycle refrigerator with superconducting devices is also under study.

7. At the University of Virginia, a group including Professors J. Beams, B. Deaver, R. Coleman, J. Pierce and G. Hess (NR 319-029) are engaged in the following theoretical and experimental investigations: (a) measurement of the electronic switching in various materials such as V_2O_3, Ti_2O_3 and Fe_3O_4; (b) study of the properties of very thin superconducting microchannels; (c) production of near zero magnetic fields and (d) study of the properties of superconducting magnetometers in prototype systems.

8. At Harvard University, Professors M. Tinkham and M. Beasley (NR 319-031) are studying the behavior of superconducting magnetometers and voltmeters operating in 2-3 kilogauss magnetic fields and at temperatures of 15-20 K. Using a superconducting voltmeter down to 10^{-15} volts, the resistive transition near the critical temperature of filamentary superconducting tin whiskers is being studied.

9. At Cornell University, Professor W. Webb (NR 319-032) is studying the behavior of various classes of superconducting magnetometers in terms of thermal and mechanical stability, temperature dependence of critical currents, current-voltage characteristics, noise performance and various design and fabricating techniques. The classes of magnetometers under study include rf and dc biased thin film types, rf and dc biased point contact types and those designed with varying dynamic inductance.

10. At the Massachusetts Institute of Technology in the National Magnet Laboratory, Dr. R. Meservey (NR 319-033) is studying, both theoretically and experimentally, wave mechanical effects in superconductors of very small dimensions (a few microns). Solutions of the Ginzberg-Landau equations for periodic structures and for doubly and multi-connected superconducting thin film geometries, in which the current density is high, are being investigated. Optical and scanning electron beam techniques are being employed for the fabrication of high resolution microstructures.

11. At the Westinghouse Research and Development Center, Dr. C. K. Jones (NR 319-034) heads a group studying the characteristics of NbN weak link superconducting bridges of various geometries. The spectral response of these devices to microwaves and far infrared radiation is under investigation, covering the range from X-band (9 GHz) on into the millimeter wave region. The properties and performance of these superconducting sensors are being studied when cooled by miniature closed cycle refrigerators.

12. At Georgetown University, Professors W. Gregory and L. Leopold (NR 319-036) are studying the characteristics of the millimeter wave radiation emitted from a new class of normal-to-superconducting point contact devices. Measurements of the line-width of the emitted radiation is being made by various techniques. Comparison of experimental results with theory is being attempted.

13. At the National Bureau of Standards in Boulder, Colorado, Dr. J. Zimmerman (NR 319-038) is studying the properties of superconducting magnetic gradiometers in terms of practical, optimum and reliable operation. Terrestrial magnetic gradient fluctuations and magnetic signals of various kinds will be measured with these devices.

14. At Stanford University, Professor T. Geballe (NR 319-044) is studying the properties of a new class of layered sandwich type superconducting tunnel junctions. In one geometry consisting of superconductor, transition metal dichalcogenide and superconductor, the Josephson tunneling current is being investigated when the layers are moved apart in controlled steps by intercalation with organic molecules.

In attempting to give a panoramic view of the various tasks in superconductivity supported by ONR, I have, in all honesty, failed to do justice to any single one. As you see, these programs vary widely in scope and depth, but they have one common goal - support research in those areas with the greatest promise of practical future utility. For the Navy, this utility lies in four vital fields: anti-submarine warfare, surveillance, communication and propulsion. As these programs in ONR continue and hopefully grow, we will forge a very tight feed-back loop between them, the efforts of the various Navy laboratories and the exploratory development interests of the commands. In addition, we in ONR have an urgent task to make the fruits of basic research in superconductivity familiar to those in the Navy who wish to consider the use of superconducting devices and materials to solve practical problems of the fleet.

SUPERCONDUCTIVITY AT NRL

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The NRL experimental program in superconductivity has been primarily concerned with basic properties of bulk superconductors since 1950. In the early days, the program involved the elements in the periodic chart almost exclusively.

There were no superconducting elements with 9, 6, or 2 outer electrons, as shown in fig. 1,[1.)] and it was assumed that superconductivity did not exist in these columns of the periodic chart. However, the work at NRL has shown this to be a misconception, since over the years, we have discovered Be (e/a = 2) with T_o of .027K; W (e/a = 6) and T_o = .012K and Ir (e/a = 9) T_o = .140, where e/a represents outer electrons per atom. Today it is generally accepted that superconductivity occurs for just about any e/a ratio except perhaps e/a = 1, where T_o will be extremely low if it indeed exists at all.

NRL got into the alloy business in the early 1960's in a collaborative effort with Westinghouse Research Laboratories. At that time, both Westinghouse, and Pippard in England, were proclaiming that NbMo alloys would be a true test of the validity of the BCS theory. We know today that NbMo did not bring the downfall of BCS.

1.) Figures 1 and 4 were kindly loaned by Prof. Rose.

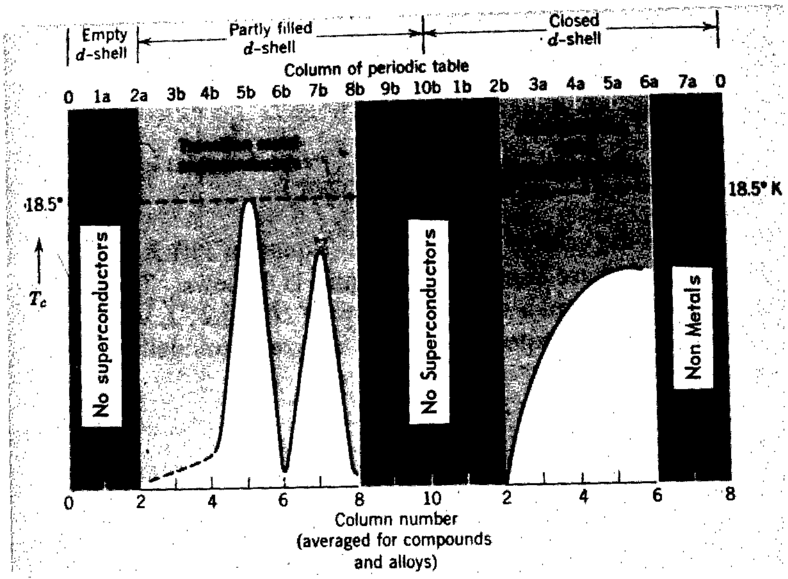

Figure 1 The variation of T_c with position in the periodic table. (From B. T. Matthias, *Progress in Low Temperature Physics*, Vol. II, p. 138, ed. by C. J. Gorter, North Holland Publishing Co., Amsterdam, 1957.)

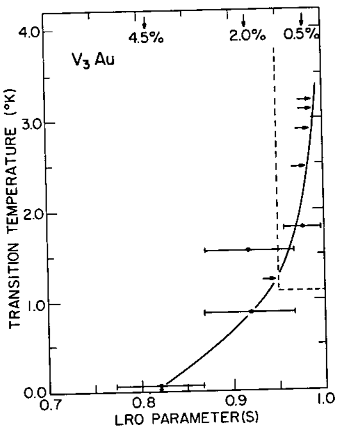

Figure 2.

Transition temperature vs. LRO parameter for V_3Au.

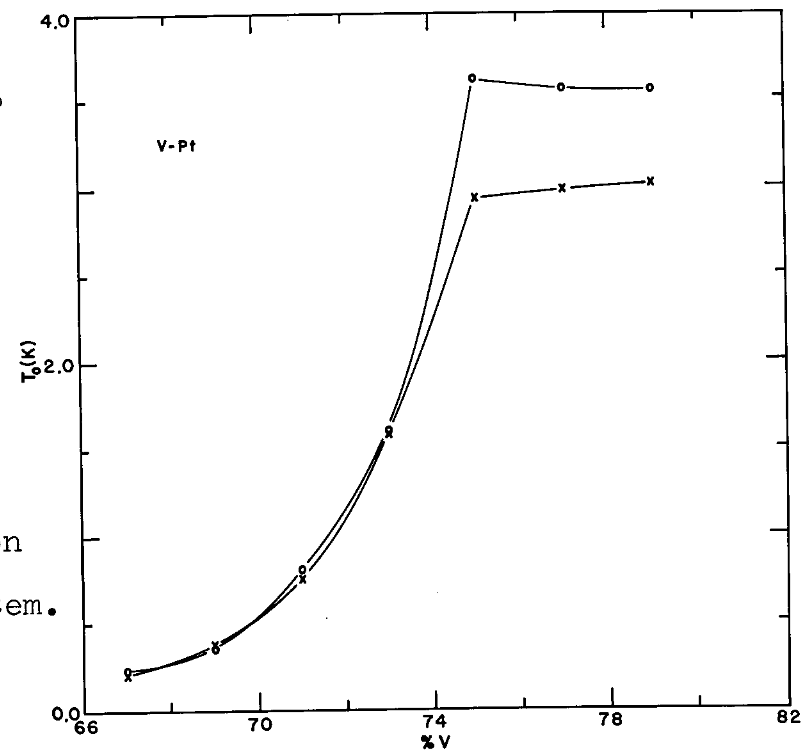

Figure 3.

T_o vs. composition for the V-Pt system.

About this time NRL became interested in a Bell Labs report that there was no isotope effect in either Os or Ru. The isotope effect states that $T_o \propto m^{\alpha}$ where α for most materials is accepted as -1/2. NRL found that for Os, α exists and is - 1/5, but for Ruthenium, $\alpha = 0$. This is of interest because superconductivity involves the phonon spectrum of the material and one would expect to see some mass dependence of T_o.

It was about this time also that Marvin Cohen predicted theoretically that degenerate semiconductors could become superconductors. Once again, collaborating with our colleagues at Westinghouse, Cohen's prediction was experimentally verified and now there are several superconducting degenerate semiconductor systems.

Chronologically, this brings us up to our current interests. As Prof. Rose indicated, the βW structure alloys are a very interesting class of superconductors. This morning it was emphasized that it is frequently beneficial to collaborate, and we embarked on a 4 laboratory collaborative effort of studying the effects of heat treating these alloys to change the long range order (LRO) of the linear chains. The effects of the change of the Bragg-Williams LRO parameter is reflected in the T_o of the samples. In this study, Richard Waterstrat at NBS made the samples, Ed van Reuth at NSRDL Annapolis made the order parameter measurements, Richard Blaugher at Westinghouse made the measurements on high T_o materials, while NRL did the low T_o work.

The literature lists various reported T_o's for many of these alloy systems, and we wanted to ascertain the cause. A good example is the V-Au System. The phase diagram indicates that this is a line compound, that is, the βW phase exists only at (or very near) the stoichiometric composition V_3Au. Thus, one can disorder (or order) this alloy by suitable heat treatment and we see the results of this study in fig. 2. We have taken one sample, divided it into 4 parts and given each part various heat treatment, such that T_o goes from less that .015K to more than 3.2K, increasing as one approaches perfect ordering indicated by S = 1. Optimum T_o for this material should occur after a 750C anneal for 4 weeks.

If we come back one element in the periodic chart to Pt and make βW phase V-Pt, we find that, in this case, we can have a concentration range. Thus we can order the sample by both alloying with increasing V concentration as well as by thermal treatment as shown in fig. 3. It is noted that once we achieve stoichiometry, i.e. V_{75} Pt_{25}, further addition of V makes very little change in T_o until you work out of the βW phase.

Again we see Prof. Rose's illustration of the βW or A_3B type material in fig. 4. In V_3Au, one can only interchange an A atom with a B atom, and that is what occurs in the thermal treatment. That is, in the as cast form, many of the A atoms occupy B sites and vice versa. However, the anneal brings about the integrity of the A atom chains. In the V-Pt System, we can do something else. Here, one can have a deficiency of V atoms, and the much larger B atoms greatly distort the chains and hence the phonon spectrum.

Another by product of these investigations will be shown in the next two figures. In fig. 5, we see another plot of the Matthias regularities,[2.)] where T_o is plotted for many alloys. It is obvious that there is no trend that can be picked out. However, in fig. 6, which shows data for the βW type alloys that we have measured, one can now see a very definitive effect. There are, indeed, peaks in T_o vs e/a, and also, for a given e/a ratio, alloys from the 4d transition series have higher T_o than do those of the 3d series.

To date, we have done much collaborating primarily for the acquisition of samples. However, we now have the in house capability to produce many samples, and we expect to become much less dependent on benefactors. This should not imply however that we will cease our collaboration, but rather, we will place different emphasis on the collaboration. For example, we are working on a problem with Dr. Goff of NOL. Since he is following me on the problem I will let him explain it, but we are making our own samples in this case.

Up until a few weeks ago, in order to work at ULT's it was necessary to use magnetic cooling techniques which, at NRL, are quite routine due to our excellent high magnetic field facility. However, Dr. Gubser has now successfully run his dilution refrigerator down to 10mK as determined by carbon resistance thermometry. This refrigerator will be used to explore some predicted effects

2.) Figure 5 appears in an article by T.G. Berlincourt in Superconductivity In Science & Technology, Marvin H. Cohen Editor, U. of Chicago Press 1968.

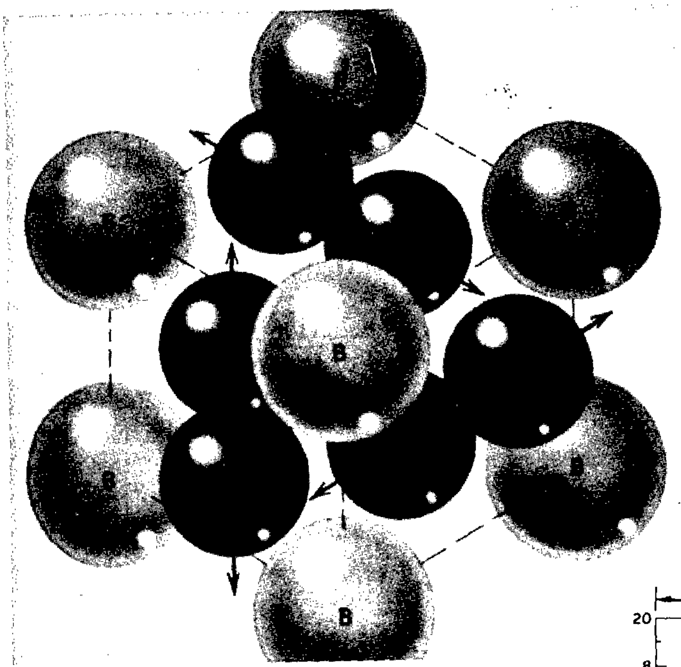

Figure 4.
Schematic drawing of the β-W structure.

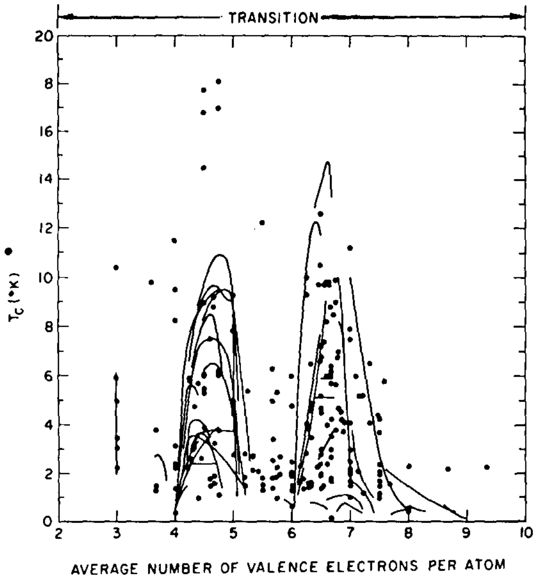

Figure 5.
T_o vs. e/a ratio for a number of previously reported alloys.

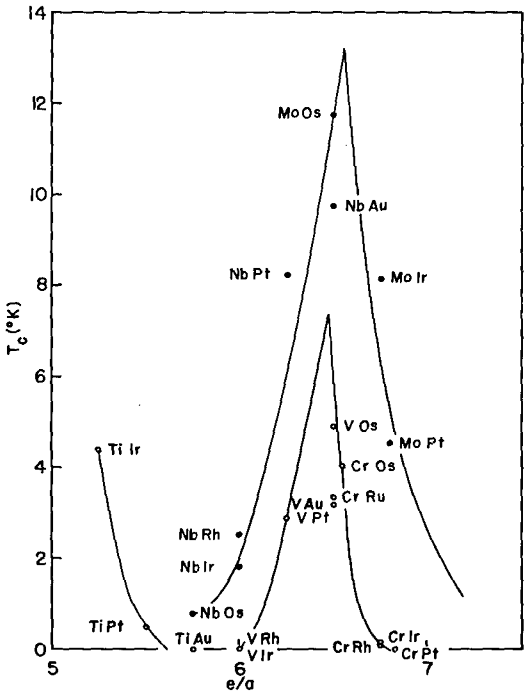

Figure 6.
T_o vs. e/a ratio from NRL investigation of β-W compounds.

regarding superconducting semiconductors.

At NRL there is an increasing interest among the scientists and engineers to conduct their experiments in a cryogenic environment. To this end, we are in the process of establishing a multipurpose cryogenic lab. When completed, we envision this lab to contain a closed cycle helium refrigerator capable of producing 4 watts at 4.2K, variable temperature dewar and a He^3 refrigerator.

It is envisioned that the first application of this apparatus will be in regard to a proposal by Mr. Hobbis of our Communication Sciences Division in the field of superconducting RF filters, cavities and possible antenna assemblies. It is anticipated that this will lead to a study of a-c losses in superconductors.

For the past 6 months Dr. Takken has been looking into the device situation, and he will soon furnish us with concrete guidelines as to what areas NRL can best make its contribution to the Navy in this ever expanding field of superconductivity technology.

NOL RESEARCH IN MATERIALS

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At the Naval Ordnance Laboratory our materials research programs are concerned with both semiconductors and metals. These programs take what I would like to call the multiview; that is, investigations are undertaken with several purposes in mind simultaneously. As a result there is a greatly increased probability that the investigation will bear fruit. Apropos to this conference, one of our goals is to study the mechanism and occurrence of superconductivity. We are concerned with the type of problem touched upon by Professor Rose at the beginning of his talk on materials: why do materials go superconducting and what affects the superconducting state? As anyone knows who has heard Professor B. T. Mattias speak[1], the subject is quite controversial. My intention today is to sketch briefly how we include this goal in our programs on the lead-salt semiconductors and transition metals.

The original purpose of the lead-salt semiconductor program at NOL was connected to their use as infrared detectors, and there has been much work done to determine their electrical properties. A few years ago Drs. Allgaier and Houston of this Laboratory, Drs. R. Hein and Gibson of NRL, and Drs. Mazelsky and Miller of the Westinghouse Laboratories[2] found that one of these salts-SnTe-became superconducting at low temperatures.

About this same time Dr. Richard Brown and Dr. Peter Scharnhorst did their doctoral thesis investigations at this Laboratory on the effect of micro-crystalline disorder on critical currents and fields of thin films of metallic superconductors[3, 4, 5, 6] - see the left side of Figure 1. This work, directed by Professor Glover of the University of Maryland, led to their degrees from that institution. They have now begun to apply these thin film techniques to the lead salts in order to explore the effect of amorphous structure on their semiconducting properties[7] - see the right side of Figure 1. It would be highly desirable to extend the measurements of these films to lower temperatures, at least in the case of SnTe, to investigate the effect of disorder on its superconducting properties. It is also possible to study the substances in the center of Figure 1 which can exist in several states of disorder and so bridge the range from metals to semiconductors in all types of disorder. One always hopes that such studies will lead to an understanding of the superconducting transition temperature.

The metals research program is concerned with the transition metals shown in Figure 2 by the darkened squares. These elements have been studied either as elements (Cr, Mn, Fe), alloys (Cr-Fe, Cr-Mo), intermetallic compounds (TiFe, TiCo, TiNi), or alloys of these compounds (TiX). The experiments consist of measurements of the transport properties (such as the thermal conductivity, thermoelectric power, electrical resistivity, and Hall effect) of these substances over the temperature range from about 1° K to 300°K. I have found that it is possible to correlate the anomalies that are almost invaribly seen in the properties of these substances with aspects of their electronic structure.[8, 9, 10] Thus it is becoming possible to use these measurements as a sort of probe of the electronic structure of these alloys and so correlate their various properties with this electronic structure.[11] This procedure promises to be superior to the more common heat capacity measurements because more of the electronic structure is observed; the heat capacity experiments see only the very dense portions of the electronic structure.

Again for our purposes today, we are interested in the superconducting properties of these transition metals. As we all know the elements of a group in the periodic table resemble each other. Thus it is expected that changes in the electronic structure that are found as one goes along the first long period, which contains Cr, Mn, and Fe, will be also found to some extent in the second and third long periods just beneath it. Indeed it is known that even the alloys of these metals behave in this same way. The really interesting observation is as Professor Rose pointed out that alloys with the same average number of valence electrons per atom have many similar properties. My experiments indicate that such is the case with the intermetallic compounds and their alloys TiX.[12] It is possible to prepare a sort of generalized periodic table shown in Figure 3 where we see that TiFe takes its place above Cr and TiNi takes its place above CrFe, the place that would be occupied by Mn (I have shown that TiNi, Mn, and CrFe have much in common[13]).

For us today, the important point is that each of the rows of Figure 3 exhibit collective interactions that in the case of the long period headed by Cr are magnetic and in the case of the long period headed by Mo are superconducting. One gets the impression that similar electronic structures are either superconducting or magnetic. In this connection we have made a very strange observation that at a valence electron per atom ratio of about 6.2 the Mo alloys exhibit high transition temperatures, the Cr-Fe alloys show some sort of electronic structure change, and the TiX alloys also become superconducting with a short composition range on either side that is ferromagnetic![14] In other words ferromagnetism and superconductivity are observed to be mutually exclusive but contiguous.

The fact that this phenomenon occurs at a composition at which peculiarities are seen in the alloy systems just below it, as shown in figure 3, implies that there is a basis for a real physical effect. Studies are now under consideration to determine whether the phenomenon involves a structural instability or an electronic structural change.

In conclusion I would like to emphasize that practical superconductors involve transition metals. The actual internal electronic structure of the alloys now used is unknown. Experiments of the sort that I have described very cursorily are designed to ferret out this structure in alloys and to correlate it with superconducting phenomena. The practical interest is the relation of this structure with the transition temperature.

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Figure 1.

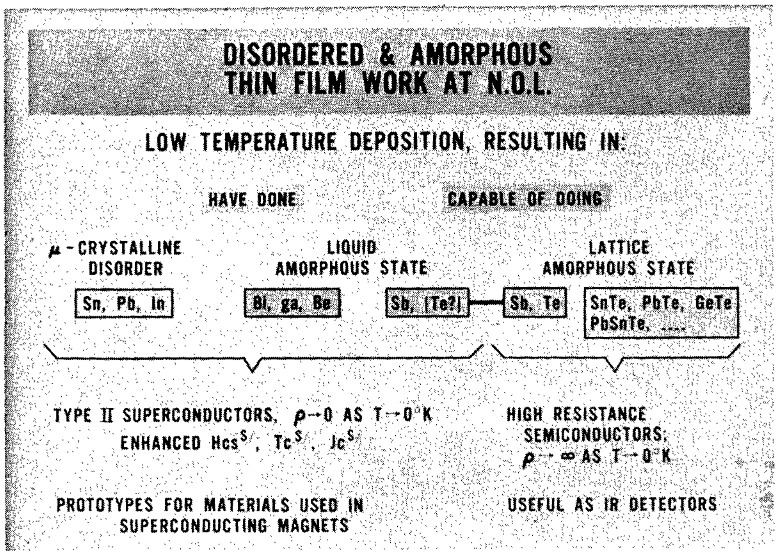
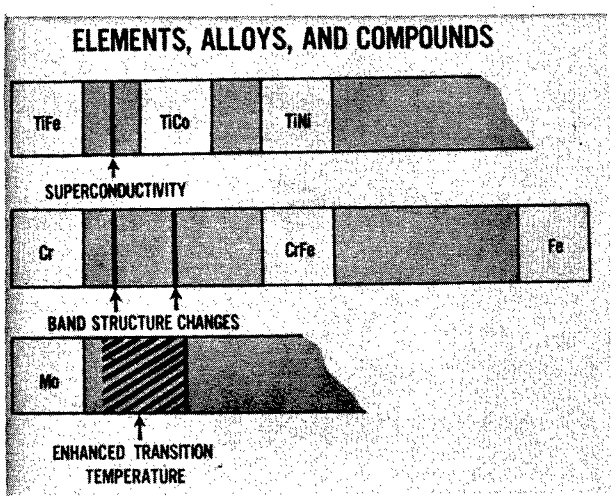


Figure 3.

Generalized periodic chart.



IA	IIA	IIIA	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIB	IVA	VA	VIA	VIIA	INERT GASES
1.0080 H 1																	4.003 He 2
6.940 Li 3	9.013 Be 4	10.82 B 5											12.011 C 6	14.008 N 7	16.000 O 8	19.00 F 9	20.183 Ne 10
22.991 Na 11	24.32 Mg 12	26.98 Al 13											28.09 Si 14	30.975 P 15	32.066 S 16	35.457 Cl 17	39.944 Ar 18
39.100 K 19	40.08 Ca 20	44.96 Sc 21	[redacted]	50.95 V 23	[redacted]						65.38 Zn 30	69.72 Ga 31	72.60 Ge 32	74.91 As 33	78.96 Se 34	79.916 Br 35	83.80 Kr 36
85.48 Rb 37	87.63 Sr 38	88.92 Y 39	91.22 Zr 40	92.91 Nb 41	[redacted]	(99) Tc 43	101.1 Ru 44	102.91 Rh 45	106.4 Pd 46	107.880 Ag 47	112.41 Cd 48	114.82 In 49	118.70 Sn 50	121.76 Sb 51	127.61 Te 52	126.91 I 53	131.30 Xe 54
132.91 Cs 55	137.36 Ba 56	138.92 La 57	178.50 Hf 72	180.95 Ta 73	183.86 W 74	186.22 Re 75	190.2 Os 76	192.2 Ir 77	195.09 Pt 78	197.0 Au 79	200.61 Hg 80	204.39 Tl 81	207.21 Pb 82	209.00 Bi 83	(210) Po 84	(210) At 85	(222) Rn 86
(223) Fr 87	(226) Ra 88	(227) Ac 89															

Key: Atomic Weight / Atomic Symbol / Atomic Number

Lanthanide Series	140.13 Ce 58	140.92 Pr 59	144.27 Nd 60	(147) Pm 61	150.35 Sm 62	152.0 Eu 63	157.26 Gd 64	158.93 Tb 65	162.51 Dy 66	164.94 Ho 67	167.27 Er 68	168.94 Tm 69	173.04 Yb 70	174.99 Lu 71
Actinide Series	232.05 Th 90	(231) Pa 91	238.07 U 92	(237) Np 93	(242) Pu 94	(243) Am 95	(247) Cm 96	(249) Bk 97	(251) Cf 98	(254) Es 99	(253) Fm 100	(256) Md 101	No 102	103

Figure 2.

Periodic chart.

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NOL'S INTEREST IN MAGNETOMETRY

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The major work accomplished that is related to applications of superconductivity has been the development of a low field magnetometer test chamber shielded with a superconductor.

A volume containing a reduced magnetic field may be obtained inside a lead foil sack by opening the folded sack at 4.2 K when the lead is superconducting. A two-stage device based upon this idea was used to reduce earth's field to below 10^{-6} oersted in a volume of several cubic inches. The superconducting sack shields this volume against the magnetic field fluctuations of the laboratory environment. The estimated noise level in the low field space is 10^{-8} oersted. A glass dewar inserted into the sack permits working in the low field space at controlled temperatures near room temperature. This system has had extensive use for the study of the long term stability of flux-gate magnetometer sensors. This work has been reported in Rev. Sci. Instr. 39, 547-550 (1968). **

Some preliminary work was carried out on the feasibility of using a superconducting magnetometer or gradiometer as an arms cache and mine detector. It was concluded than an aggressive and very well supported program would be required to develop a useful superconducting magnetic detector.

** Work on a flux-gate magnetometer that demonstrates use of the test chamber is reported in IEEE Trans. on Magnetics Vol. MAG-4, No. 3, Sept. 1968.

THE INTEREST IN SUPERCONDUCTIVITY AT THE NAVAL UNDERSEA RESEARCH AND DEVELOPMENT CENTER

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My talk will be unclassified, highly speculative, and I hope very brief. We're not at present doing any work in superconductivity at NUC. We are primarily working on ASW systems, particularly sensors, fire-control systems, and the platforms on which they're mounted. The reason we're interested in superconductivity right now is that we see a possiblility of getting the refrigeration almost for free, at least if we're willing to use liquid hydrogen. Our laboratory is monitoring proposals which have been solicited from industry on advanced concepts in submarines. Many of these involve an idea mentioned by Dr. Levedahl-that is, a mothership which would launch and retrieve small submersibles which would carry sensors and possibly some of the weapons systems. Some of the propulsion systems proposed for these small submersibles make use of liquid hydrogen and liquid oxygen. The cryogenic fluids would be produced in large quantities on the mother-ship. The question I would like to pose is, if we have liquid hydrogen available, what can we use it for in addition to propulsion? Well, at its boiling point of 20°K, it appears there isn't much we can do with it right now. If, however, we pump it down to the triple point at 14°K, which Professor Daunt assures me is a relatively easy thing to do, it looks as though we could make good use of the beta-tungsten or the rock salt structure superconductors. Nb_3Sn has an H_{C2} of the order of 100, 000 gauss at 14°K, and the niobium-aluminum-germanium alloys are reported to have H_{C2}'s of about 200, 000 gauss although they're probably not ready for device use yet.

Certainly, though, Nb_3Sn is very useful and its technology is well developed. Also, I believe all of our speakers this morning indicated that most of the quantum devices would operate at this relatively high temperature.

Assuming, then, that superconducting devices can function near the triple point of hydrogen, what uses do we want to make of them? Let me indicate roughly the type of submarine system we are thinking about. We have in the vehicle cryogenic liquid tanks, a propulsion system might use fuel cells and electric motors, direct burning of the gasses, or even a magnetohydrodynamic system using superconducting magnets. There are many problems of interest in this field, but I'm more familiar with the sensor and signal processing systems s so I will emphasize these areas.

We see three interesting uses of superconducting devices as sensors although there may be many more. Our work is primarily in acoustics, and one of the biggest problems in underwater acoustics is the severe attenuation of high frequency sound. It is difficult, though, to get enough energy into the water at more desireable low frequencies using conventional techniques. It appears that using a superconducting magnet one might be able to make a moving coil type transducer which would operate efficiently at low frequency. The subject of magnetometers has already been discussed in considerable detail by,experts in the field. I only want to add that, in view of the sources of magnetic noise which were enumerated this morning, a small submarine would seem to offer a good platform for a sensitive magnetometer. The geomagnetic noise and surface wave noise will be strongly attenuated at any reasonable depth beneath the surface. The geologic noise caused by moving over magnetic deposits on the ocean floor will be pushed into an entirely different region of the frequency spectrum from where it occurs in aircraft systems. Platform noise would, of course, still be present, but, if this problem can be solved for aircraft, presumably it can also be solved for a submarine. Finally, we come to a type of sensor which I don't believe has been mentioned as yet, possibly because it is just not feasible. However, Prothero and Goodkind at the University of California at San Diego have developed a superconducting gravimeter which they claim has very high sensitivity and good stability over time. I'm not sure if it has been achieved yet, but they hope for a sensitivity of the order of 10^{-12} of g. Certainly, measurement of the gravitational anomaly seems a far out way of detecting a submarine, but we feel it ought to be considered. There is even a possibility that a time varying component due to the rotation of the propellor might be detectable.

The second area in which we see possible applications of superconductivity is in the processing of information derived from the sensors. Much of our signal processing involves the use of ultrasonic delay lines of various types. At low temperatures, the attenuation of acoustic waves in most materials is greatly reduced. A particularly drastic decrease occurs below T_c in certain superconductors. This suggests the possibility of delay lines with much larger time-bandwidth products than are possible with room temperature devices. In addition, the direct generation of microwave frequency acoustic waves from electromagnetic waves through the interaction with helicons has been demonstrated in superconducting indium films. Finally, the very high Q's attainable with superconducting microwave cavities offer possibilities in the very narrow band analysis of the passive acoustic signatures of targets. It may appear strange to consider superconducting cavities, which operate at very high frequencies, for processing low frequency sonar data. The reason is, of course, that the signal processing is done in compressed time so that we do get into the frequency range where these devices are useful.

In summary, I want to suggest again that, in the design of small submarines in which cryogenic liquids are available for use in the propulsion system, many other uses of cryogenic techniques may present themselves which might not otherwise be worth the cost of the necessary refrigeration.

DISCUSSION

Dr. Takken, NRL: The gravimeter of Prothero and Goodkind can only be made sensitive in the direction of the earth's magnetic field.

Dr. Young: I see. Well, that limits it somewhat, but I don't think is rules it out as a possibility.

Mr. Jablonski: Do the magnetometer ranges that you might hope for sound operationally useful for submarine to submarine detection? I sort of feel you wouldn't want to be that close.

Dr. Young: Possibly not, but I think there may be applications for which such ranges may be acceptable. Also, longer ranges may be feasible than from aircraft because of the different noise background.

Mr. Edelsack: Some ideas have been considered of following-where you have a mission of about 2 or 3 hours and you just want to trail something. Perhaps in those kinds of missions magnetometry offers some help.

Dr. Hein, NRL: If I understand it correctly, you're proposing to use liquid hydrogen and pump on it.

Dr. Young: That's right.

Dr. Hein: Suppose you pump down to about 14.5°K, then you're using a reduced temperature of about 0.8 with the best known superconductor. You won't have near the full energy gap in this case, and I don't know of any devices that work at a reduced temperature of 0.8 for a type II superconductor.

Dr. Young: I can only say that Dr. Mercereau indicated this morning that he thought they would work at 14 degrees.

Dr. Hein: Okay. One other comment, the Q's of these cavities may be greatly lowered at a reduced temperature of 0.8.

Dr. Young: Well, the good cavities have Q's about 6 orders of magnitude above what you can get with conventional cavities. I'll give you a couple orders of magnitude, or is it worse than that?

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PROGRAM

PART I (Unclassified)

Session A — Dr. Robert A. Hein, Chairman
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Properties of Superconductivity
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Superconducting Materials: Processing and Properties
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Cryogenic Refrigerators
Professor John Daunt
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Session B — Mr. Arthur Chaikin, Chairman
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Superconducting Electric Machinery
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Survey of Superconducting Magnet Technology
Dr. David Coffey
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Session C — Mr. F. B. Isakson, Chairman
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Submillimeter Josephson Effect Devices
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Magnetic Field Measurements Using Superconducting and Conventional Devices
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Session D — CAPT William F. Sallada, USN, Chairman
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Superconducting Thin Film Mini-Circuits
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Superconducting Systems for Magnetic Anomaly Detection
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Navy Uses of Cryogenic Systems
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Discussion and Summary
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PART II (Secret)

Session E — Mr. Frank E. Jablonski, Chairman
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Superconducting Machinery Propulsion Program and Plans
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Management Views on Superconductivity in the Navy
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Electric Propulsion Concepts
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The Shaped Field Electric Drive Concept
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An AC Superconducting Marine Propulsion System
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Development of a Synchronous Generator Using Superconducting Field Windings
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Session F — Dr. C.C. Klick, Chairman
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Superconductivity Research in ONR
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Superconductivity at NRL
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NOL Research in Materials
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NOL's Interest in Superconducting Magnetometers
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Radiation Effects on Superconducting Devices
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The Interest in Superconductivity at the Naval Undersea Research and Development Center
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Session G — Dr. Robert C. Allen, Chairman
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Superconducting Magnetic Sensors in Search and Surveillance
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A Minesweeping Application of Superconductors
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Superconducting Magnetic Minesweeping Concepts
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Some Possible Applications of Superconductivity in Mine Countermeasures Systems
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Superconductors in Antisubmarine Warfare
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Superconducting Gradiometers in MAD
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Discussion and Summary
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13. ABSTRACT

This workshop on Naval Applications of Superconductivity was jointly sponsored by the Chiefs of Naval Research and Naval Development. Present were representatives, military and civilian, from research and development groups in the Navy concerned with present and future applications of superconducting materials, devices and systems. For the first time, engineers, administrators, scientists and fleet personnel — all with a common interest in superconductivity — met in one place for a period of two and one-half days to engage in a free and frank exchange of ideas, to review existing programs, and to discuss future plans. In addition, the workshop provided an unique opportunity to collect the opinions and comments of experts from industry and universities regarding the current status and future prospects of various areas of superconducting technology which relate to naval requirements.

The program was divided into two parts, with a total of seven sessions. Part I, consisting of four sessions, was unclassified and contained ten invited papers plus discussion and summary. There were about 95 persons at these sessions, including Navy and non-Navy attendees. Part II, consisting of three sessions, was classified secret and contained some 21 contributed papers. Attendance at these three sessions was limited to Navy personnel, who numbered about 75.

The manuscripts of the talks were either directly supplied by the speakers or were edited by the speakers from transcriptions of their recorded talks. The proceedings have been prepared for publication at the Naval Research Laboratory and are issued as NRL Reports 7302 and 7303. The first report is unclassified and

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Detectors						
ASW Detectors						
Magnetic Anomalies						

contains the invited papers given in Part I in the order in which they were presented, followed by a summary and lightly edited discussion. This report also contains a few of the contributed unclassified papers which were presented in Part II. The second report, classified secret, contains all classified papers presented during Part II, plus those unclassified papers whose subjects relate to material discussed in the classified papers. The material presented in the classified sessions is included in its entirety, with the exception of information of a management nature.